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DOE HEP Grant Closeout Report

from

Duke University High Energy Physics

to

Department of Energy Office of Science

Project Title: Research in High Energy Physics at Duke University

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DUKE HEP PROJECT DESCRIPTION

Contents

1 ABSTRACT

This is the Closeout Report for the research grant in experimental elementary particle physics, carried out by the Duke University High Energy Physics (HEP) group. We report on physics results and detector development carried out under this grant, focussing on the recent three-year grant period (2010 to 2013). The Duke HEP group consisted of seven faculty members, two senior scientists, five postdocs and eight graduate students. There were three thrusts of the research program. Measurements at the energy frontier at CDF and ATLAS were used to test aspects of elementary particle theory described by the Standard Model (SM) and to search for new forces and particles beyond those contained within the SM. The neutrino sector was explored using data obtained from a large neutrino detector located in Japan, and R & D was conducted on new experiments to be built in the US. The measurements provided information about neutrino masses and the manner in which neutrinos change species in particle beams. Two years ago we have started a new research program in rare processes based on the Mu2E experiment at Fermilab. This research is motivated by the search for the $\mu \to e$ transition with unprecedented sensitivity, a transition forbidden in the standard model but allowed in supersymmetric and other models of new physics.

The high energy research program used proton and antiproton colliding beams. The experiments were done at the Fermilab Tevatron (proton-antiproton collisions at a center of mass energy of 1.96 TeV) and at the CERN Large Hadron Collider (proton-proton collisions at 7-8 TeV). The neutrino program used data obtained from the Super-Kamiokande detector. This water-filled Cherenkov counter was used to detect and measure the properties of neutrinos produced in cosmic ray showers, and from neutrino beams produced from accelerators in Japan. The Mu2E experiment will use a special stopped muon beam to be built at Fermilab.

2 Introduction

The Duke High Energy Physics Group has been carrying out elementary particle research for over forty years. Initial experiments used bubble chambers, with a transition to electronic fixed target experiments in the 1970's. The current program is focused on measurements using hadron colliders, high energy neutrino beams and a stopped muon beam. The active experiments have been:

- CDF at the Tevatron (since 1990)
- ATLAS at the LHC (since 1995)
- Neutrino physics at Super-Kamiokande and T2K (since 2004)
- Search for rare processes at Mu2E (since 2011)

Our collider-physics research program transitioned from CDF at the Tevatron to the ATLAS experiment at the LHC. We conducted studies of electroweak, exotics, Higgs and top physics. A technical coherence was achieved through Duke's contributions to charged particle tracking at CDF (the Central Outer Tracker) and ATLAS (the Transition Radiation Tracker). The research programs at ATLAS and CDF were carried out by five Duke faculty members (Professors Arce, Goshaw, Kotwal, Kruse, Oh), two senior scientists, three postdocs, and typically six graduate students. These activities were funded by a single umbrella Task A.

In January 2010, Assistant Professor Ayana Arce joined the Duke physics department and the HEP Group. She continues her research program on ATLAS.

Neutrino research was established at Duke in 2004 with the addition of two new faculty positions (Professors Scholberg and Walter). The Duke Super-K program will continue and the K2K (neutrino beam from KEK to Super-Kamiokande) program has evolved into T2K (a new high-intensity off-axis neutrino beam from Tokai to Super-Kamiokande). The Neutrino group is now involved with LBNE in the US. Two faculty members, two postdocs and two students carry out the research. The neutrino research program is described under Task N.

Research on rare processes at Fermilab's intensity frontier was established at Duke in 2011 by Prof. Oh and one senior scientist on the Mu2E experiment. This research program, currently focussed on the tracker R&D, is described under Task M.

2.1 Summary of Research Activities

Sections 3 through 8 of this document contain the detailed project descriptions of our research programs carried out by each PI. We include here a summary of physics goals and contributions Duke has made to each of the experiments.

2.1.1 Research at CDF

Research work at the Fermilab Tevatron using the CDF detector has been a central part of the Duke HEP program for over 16 years. We have been active in four physics analysis areas:

- Electroweak physics (W mass, di-boson production)
- Top quark physics
- Higgs boson searches
- Search for exotica (charged massive particles, excited leptons, new gauge bosons)

Although diverse research topics, there was a coherence through the use of high-P_T leptons and W/Z bosons as the basic physics objects. The measurements require precision tracking information, which is one of the strengths of the Duke HEP group. Duke physicists have served as physics co-conveners of the Higgs, top, electroweak and QCD physics groups. We also made significant contributions to the construction and operation of the CDF experiment:
• Central Outer Tracker (COT) construction and maintenance
• Silicon Detector (SVX II) construction and maintenance
• Online and Offline Operations Managers
• Deputy Leader of the Run IIb Upgrade Project (2002 - 2006)
• Co-leader of the particle tracking group (2002 - 2006)
• Co-leader of data-handling group (2005 - 2006)
• Co-leader of the GRID computing group (2007 - 2008)
• Co-leader of the Offline Software and Computing Project (2004 - 2006)
• Co-spokesperson (1997- 2003)

2.1.2 Research at ATLAS

In the last three years, the dominant part of Duke's hadron collider physics program has been at the CERN LHC using the ATLAS detector. We have made major contributions to the design, construction and installation of the barrel Transition Radiation Tracker:
• Construction of 50% of the barrel TRT modules at Duke
• Assembly of barrel support structure at CERN
• Installation of TRT modules at CERN

We have also played major roles in TRT reconstruction software and alignment, software commissioning, alignment of silicon detectors and global inner detector alignment, Monte Carlo simulation, electron-photon reconstruction, and USATLAS computing and management:
• TRT software group co-leaders
• $E\gamma$ group co-leader
• USATLAS and ATLAS Tier 3 project co-leader
• USATLAS Institutional Board Chair
• MC production coordinator
• ATLAS Upgrade Physics Sub-Committee
• US ATLAS Physics Advisor

We are working on the ATLAS upgrade, through investigation of the physics case, simulation and the upgrade of the silicon tracker. We have a number of published and ongoing physics analyses ranging from measurements of electroweak processes to searches for new physics at high-p_T.

2.1.3 Neutrino Research

Duke's neutrino physics program is focused on Super-Kamiokande and the ongoing T2K off-axis beam experiment, along with design work on future experiments including LBNE.

We have been active in:
• Super-K atmospheric ν oscillations, including three-flavor, CPT violation and τ appearance analyses
• Beam neutrino oscillation analyses, including first indications of non-zero θ_{13}
• Supernova neutrino physics studies for LBNE (physics working group convener)

Our service work has been extensive and primarily in support of our physics interests. Recent and ongoing responsibilities include:
• US group onsite maintenance for SK
• Outer detector PMT calibration, data quality control and simulation for SK
• Outer-detector-based reconstruction and event selection software for SK and T2K
• Reconstruction software, including ring-counting and particle ID for SK and T2K
• Energy scale calibration and MC production for SK and T2K
• Oscillation analysis tools for SK
• Offline co-convener for SK (2007-)
• T2K-SK, T2K-LB group co-convener (2008-)
• LBNE Water Cherenkov simulation group co-convener (2009-2012)
• LBNE Executive Committee (2010-2013)

2.1.4 Rare Processes Research

Duke's research program in this area is based on the Mu2E experiment at Fermilab. We have been active in the R&D on the straw tracker which is at the heart of the experiment. The Duke group has expertise in straw trackers after building the ATLAS barrel TRT and is playing a leading role in the Mu2E straw tracker effort.

2.2 Summary of Personnel

We summarize in Table 1 the Duke HEP research personnel and the distribution of their research efforts.

3 Task A - Ayana Arce

Graduate Students: Lei Li, David Bjergaard
Undergraduate Students: Travis Byington, Laura Dodd, Andrew Ferrante (Physics Department); Stefan Cafaro, Jake Sganga, Ben Trautman (Engineering)

3.1 Introduction

This section describes the recent accomplishments and goals of the research program directed by Arce. After joining the Duke Physics department in January 2010, Arce established an

Name	Position	Fraction of research effort			
		CDF	ATLAS	Neutrino	Mu2E
A. Arce	Assistant Professor		100%		
A. Goshaw	James B. Duke Professor	10%	90%		
A. Kotwal	Professor	20%	80%		
M. Kruse	Associate Professor	20%	80%		
S. Oh	Professor		70%		30%
K. Scholberg	Professor			100%	
C. Walter	Associate Professor			100%	
D. Benjamin	Senior Research Scientist		100%		
C. Wang	Senior Research Scientist		15%		85%
A. Bocci	Postdoc		100%		
B. Jayatilaka	Postdoc	100%			
G. Yu	Postdoc		100%		
A. Himmel	Postdoc			100%	
T. Akiri	Postdoc			100%	
Z. Li	Graduate Student			100%	
T. Wongjirad	Graduate Student			100%	
D. Bjergaard	Graduate Student		100%		
B. Cerio	Graduate Student		100%		
K. Finelli	Graduate Student		100%		
L. Li	Graduate Student		100%		
M. Liu	Graduate Student		100%		
C. Pollard	Graduate Student		100%		
C. Zhou	Graduate Student		100%		
J. Westerfeldt	Staff Assistant	15%	50%	35%	
J. Fowler	Engineer			100%	

Table 1: Summary of personnel.

ATLAS research effort focusing on simulation infrastructure and opportunities for constraining new models with leptons and with heavy particles that decay hadronically. This work has proceeded so far without direct DOE support.

Research highlights Our current research program is divided into three sub-projects: improvements to the ATLAS simulation, searches for non-Standard Model phenomena in ATLAS data, and involvement in the phase-II upgrade of the ATLAS inner tracker. The work with the ATLAS simulation group established two essential tools for ATLAS measurements and discoveries for the 7 and 8 TeV collider runs: a calibrated fast calorimeter simulation, and a conditions-dependent Monte Carlo production framework (RunDMC). In analysis, we contributed directly to searches and measurements in top and exotic physics, including the first top quark cross section measurement, limits on new phenomena using same-charge dilepton signatures, and applications of boosted hadronic object tagging to search for massive resonances decaying to $t\bar{t}$. Current analysis activities focus on substructure variables and boosted object tagging. Finally, a project co-led by Arce, Benjamin and Kruse to work on the electronics for the silicon strip-based inner tracker upgrade has enabled Duke to contribute to the software infrastructure for the ATLAS silicon strip upgrade test framework, as well as to tests of silicon upgrade hardware prototypes.

Undergraduate training is a focus of this group, which has included three recently graduated undergraduate students from the physics department, three engineering students (co-mentored with Kruse on the upgrade project), and also two summer students through the NSF REU program.

3.2 ATLAS Monte Carlo and Simulation infrastructure

3.2.1 The RunDMC simulation infrastructure (Arce, Li)

Our most far-reaching contribution to the simulation totally revised the treatment of time-dependent accelerator and detector effects, including pileup and non-collision backgrounds (detector signals arising from beam-gas, beam-halo, and cavern ricochet events) within ATLAS. Trigger configurations, hardware status, and other time-dependent detector conditions also affect ATLAS performance, and the combination of more than one time-varying effect can cause systematic effects in many measured particle properties that cannot be accounted for using time-averaged detector performance in the simulation.

To address this issue, we developed a new run-dependent Monte Carlo framework called *RunDMC* which can model detector hardware, DAQ conditions, and pileup effects simultaneously with the granularity of a luminosity block (a period roughly 30 seconds in length). Arce's role of RunDMC Framework Coordinator involved developing the software infrastructure to produce these datasets in collaboration with the pile-up tools authors in the simulation group, and coordinating the development of user analysis tools and validation tools to verify that the increasingly detailed simulation matches data performance. **Li** was involved in early validation of the calorimeter modeling, establishing the usefulness of RunDMC during a key period of hardware failures in the LAr calorimeter. From the initial pilot infrastructure (MC10a), which addressed in-time pileup variations, to the current tool used in MC12, which also includes various sub-detector and trigger conditions and bunch-by-bunch luminosity variations over time, the tool has kept up with ATLAS requirements for accurate detector simulation, and is used in nearly all of the collaboration's Monte Carlo production to model typical luminosity and detector conditions for several distinguishable datataking periods annually.

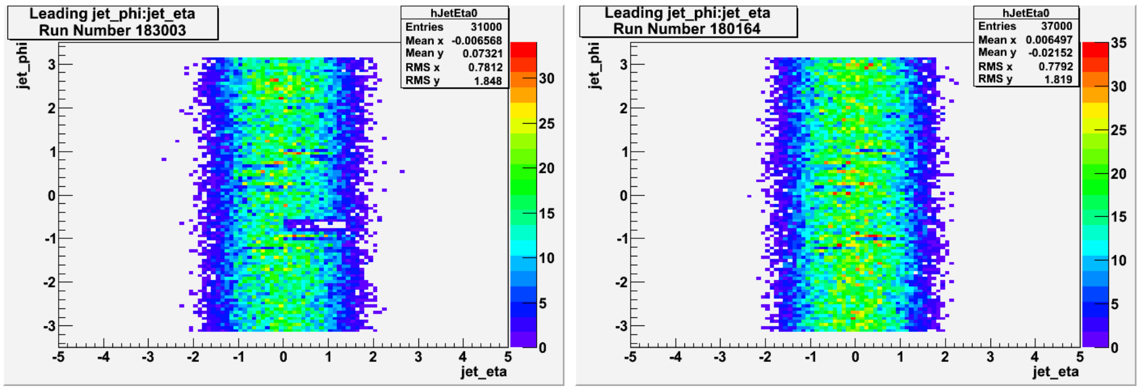

Figure 1: Calorimeter cluster occupancy for two RunDMC simulated runs corresponding to real data with and without LAr hardware failures. (**Li**)

The RunDMC infrastructure, which is also the basis for the event-to-simulation conditions matching in the alternative "zero-bias overlay" pileup simulation scheme, is in a steady state. Ongoing development mostly involves improvements to the functionality and user-friendliness of RunDMC tools, the creation of RunDMC configurations for each Monte Carlo production campaign (a few times annually), and creation of special configurations to explore systematics and to plan for future changes in LHC running conditions, including special high-pileup scans.

3.2.2 Monte Carlo generators (Arce, Li)

We have undertaken two projects with the Monte Carlo generators group: a new set of generator tunes using data extending to higher p_T scales, and a tool for validating new Monte Carlo sample requests. New signal processes and new tools for generating all processes in LHC collisions can be configured by any ATLAS user, but choosing configurations for large-scale Monte Carlo production demands careful expert oversight so that production resources are not wasted. **Li** has begun developing tools for the ATLAS Monte Carlo generator infrastructure to create and archive validation distributions for all new Monte Carlo requests. This validation infrastructure will be used to assess the usefulness of new generator configurations before submitting large jobs for production. The library of key distributions for different generators and processes will also be a new analysis planning tool in ATLAS. **Li** is also characterizing and optimizing the modeling of higher p_T data, especially production of $t\bar{t}$ events, by the the next-to-leading order generators which are used in top studies and searches for Higgs production in association with $t\bar{t}$ pairs. She is using ATLAS measurements to constrain the parton shower parameters in these event generators as part of a larger effort to update the generator tunes used by ATLAS.

3.3 ATLAS physics analysis

3.3.1 Top and exotic physics

With Berkeley, we authored and then implemented a conservative analysis strategy to determine the $t\bar{t}$ cross section with minimal dependence on uncalibrated detector performance and uncertain background predictions (**CERN-OPEN-2008-020 (2009) 925**). This early analysis led to a combined measurement of $\sigma_{t\bar{t}}$ for proton collisions at 7 TeV, consistent with predictions within the 40% uncertainty (**EPJ C 71 (2011) 1577**). Our group then began to focus on new kinematic regime, where top quarks are boosted and their decay products overlap. For this analysis, we helped develop and validate the "TopBoost" D3PD data format so that top analysis tools could be applied to these events, leading to a search for heavy resonances in $t\bar{t}$ decays (**arXiv:1207.2409**). (Pollard's contributions to these resonance searches in semileptonic and dilepton channels are described in Section 5).

Working with a Duke graduate student (Cerio), we also developed techniques to calculate fake electron rates from material interactions in same-sign dilepton candidate events in the first 34 pb^{-1} of collision data (**JHEP 1110 (2011) 107**). For a model-independent limit using 1.6 fb^{-1} in collaboration with Berkeley/LBNL and Lund we also defined a fiducial acceptance region that could be applied to various searches, and studied the two-electron channel extensively, but here, the dimuon channel proved more sensitive and led to strong limits on doubly-charged resonances and microscopic black hole production [1, 2].

3.3.2 Jet Substructure (Arce, Li, Bjergaard, Dodd, Huff)

Our current research focus is to establish new measurement techniques to decipher hadronic decays. Many processes produce energetic jet signals at the LHC: quarks, gluons, and high p_T massive particles from the primary collision, as well as accidentally overlapping clusters and calorimeter noise from pileup events. In this environment, knowing the origin of jet signals and their relationship to other jets in the event is of key importance. Within ATLAS, our group has pioneered new analysis possibilities in this area: in 2011, we formed a group (Arce, **Dodd, Li** and collaborators from NYU and DESY) to investigate color-flow [3] based observables, jet pull and dipolarity, which can help associate or identify jet pairs and jets from color-neutral resonances. While jet pull observables show promise for classifying jets in the semileptonic channel of top pair-production events, they are very sensitive to poorly-constrained Monte Carlo generator parameters. **Huff** undertook a 2012 study of Monte Carlo generator observables that can be used to constrain these parameters with reconstructed $t\bar{t}$ events; our group plans to produce these constraints as a measurement in 2012 data. Arce and **Bjergaard** continued this work as principal contributors to the 2012 BOOST Working Group Report study assessing Monte Carlo modeling of several substructure variables. This study included both color-flow observables and and *jet charge*, which is a technique for determining the electric charge of strongly interacting particles and hadronically decaying resonances. The analysis of jet charge in this (non-ATLAS) paper led to an ATLAS study of jet charge by Arce, Bjergaard, and SLAC collaborators. Bjergaard is characterizing jet charge in W+jets events in a note aimed for 2013 summer conferences. The W enables an independent tag of the leading jet's charge, allowing us to directly measure the properties of jet charge observables for single quarks for the first time at ATLAS.

Arce and **Li** are applying jet substructure observables to searches for boosted hadronic resonances. With collaborators from BNL, Geneva, Tokyo and the University of London, we have developed a boosted W/Z-boson tagger, which we are calibrating in $t\bar{t}$ events that produce one hadronic W decay. We apply this tagger to search for resonances decaying to W and Z, extending the reach of other diboson resonance searches to higher resonance mass.

3.4 ATLAS silicon tracker upgrade

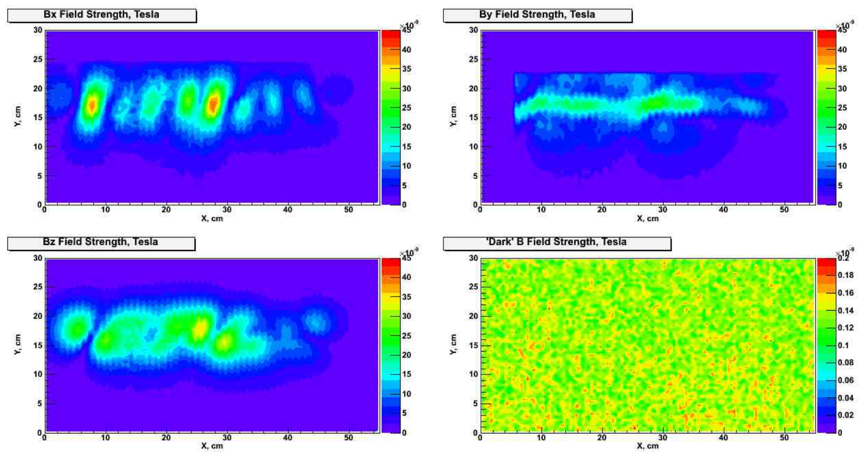

Figure 2: The magnetic field measured with a near-field probe scanning in x and y over a powered or unpowered (lower right) stavelet. (**Miller**)

We are also preparing for the phase-II upgrade of the ATLAS inner tracker (with Benjamin and Kruse). The essential components of the silicon strip upgrade, *staves*, are described in Section 6. The staves support the silicon strip detectors themselves, which are bonded to binary readout chips on an integrated hybrid circuit, and also support detector powering and cooling services and the electronics interface of each stave to the ATLAS readout system. Staves themselves hold up to twelve identical modules. The scale of the upgraded silicon strip tracker makes powering each module individually impractical, so both serial powering and DC-DC conversion using switching regulators are considered.

Supported largely by a grant from the Lord Foundation, our group has acquired and set up key components of a DAQ system for strip module testing, based on a high-speed I/O board (HSIO) developed at SLAC using an FPGA for flexible DAQ and analysis operations. Undergraduate students supported by the Lord grant (**Cafaro, Sganga, Trautman**) and NSF funds (**Miller**) played a key role in configuring this system to test a single readout chip, and helping the LBNL group to configure their own. In collaboration with Todd Huffman (Oxford), Miller also tested a DC-to-DC powered four-module "stavelet" at CERN to see if the switching currents in the DC-DC shunt regulators on each hybrid caused notable electromagnetic interference (Figure 2) or noise in the chip readout.

References

[1] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **85**, 032004 (2012) [arXiv:1201.1091 [hep-ex]].

[2] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **709**, 322 (2012) [arXiv:1111.0080 [hep-ex]].

[3] J. Gallicchio and M. D. Schwartz, Phys. Rev. Lett. **105**, 022001 (2010) [arXiv:1001.5027 [hep-ph]].

4 Task A - Alfred Goshaw

Senior Staff: Alfred Goshaw (co-PI), Doug Benjamin and Andrea Bocci
Graduate Students: Jianrong Deng, Mia Liu and Meg Shea
Undergrad Students: Will DiClemente, Josh Loyal, Jack Mattucci, Yu Sheng Huang

This report reviews our group's research activities over the past three years within the CDF and ATLAS collaborations. Research at CDF was completed in 2012 and all current activites are associated with the ATLAS experiment. There are three major parts to our research program: measurements of di-boson production to test Standard Model (SM) electroweak predictions and to search for new phenomena; service activities that support the ATLAS detector and physics program; and management responsibilities within the US ATLAS operations program. These research activities were directed by three staff members: Goshaw (based at Duke), Benjamin (based at ANL and CERN) and Bocci (based at CERN). We work closely with the Duke research programs directed by Kotwal and Kruse as there are many topics of common interest in physics analyses and technical support of the ATLAS experiment.

During this grant period seven students participated in our research program. Deng completed her Ph.D. thesis using data from the CDF experiment. Liu is a fourth year graduate student who has been studying $W\gamma$ production and will explore W boson structure through limits on the WWγ triple gauge coupling. She will complete her PhD research in 2014 based on the full 2012 ATLAS data set. Shea is a first year graduate student who worked with us for the first time in 2012. Undergraduate students contributed significantly to our research productivity. They identify research projects early in their careers and carry through projects that result in senior theses that are of publishable quality. During this grant period four undergraduate students worked with us on various ATLAS research projects. The salaries and travel of the undergraduate students were supported from a Duke University grant and other government sources independent from this DOE/HEP grant.

4.1 Electroweak Physics at CDF and ATLAS

The Standard Model predicts self couplings of the W boson, the Z boson and the photon through the non-Abelian $SU(2)_L \times U(1)_Y$ gauge group of the electroweak sector. Experimental tests of these predictions have been made in hadro-production ($p\bar{p}$ and pp) collider experiments through the s-channel production of one of the gauge bosons and its subsequent coupling to final state boson pairs such as WW, WZ, ZZ and $W\gamma$. The production cross sections are sensitive to the couplings at the triple/quartic gauge-boson vertices and therefore provide direct tests of the SM's predictions. Modifications of the gauge-boson couplings from the SM predictions could occur from a composite structure of the W and Z or new s-channel bosons that decay to the SM vector bosons pairs.

We summarize here various precision tests of the SM, searches for new physics through affects of anomalous triple/quartic gauge couplings, searches for new massive vector bosons and the establishment of limits on the rare Zγ decay mode of the recently discovered Higgs boson.

4.1.1 Electroweak research at CDF: Benjamin, Bocci, Deng, Goshaw

We have been involved with research at the Tevatron with the CDF experiment for over 15 years. During that time Duke scientists have held various leadership positons. In particular Goshaw was CDF Co-Spokesperson for six years, Benjamin and Goshaw were electroweak di-boson co-conveners and Deng and Bocci graduated with PhD theses based on electroweak physics topic. In this report we describe the closeout of our research activities at the Tevatron, resulting in a series of publications on electroweak physics topics. These measurements use $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions to produce electroweak di-bosons (WW, WZ, Wγ and Zγ) and were used to test various SM electroweak predictions. Using CDF Run II data we published on the average one paper per year on electroweak di-boson physics where we with other Duke colleagues were the primary authors. The eight most recent publications are listed in reference [1]. The devlopment of our research program in electroweak physics at the LHC was based upon the experience we gained at the Tevatron with the CDF experiment. During this grant period our research moved completely to LHC physics using the ATLAS detector.

4.1.2 Overview of electroweak research at ATLAS: Benjamin, Bocci, DiClemente, Goshaw, Liu and Loyal

We (Bocci and Goshaw) were editors of the di-boson section of early pre-data taking ATLAS performance studies and helped organize the electroweak subgroups that deal with $W\gamma/Z\gamma$ physics. We were editors of the first ATLAS publication of $W\gamma$ and $Z\gamma$ production properties using 35 pb^{-1} of $\sqrt{s} = 7$ TeV pp collisions [2]. Benjamin, Bocci, DiClemente, Goshaw, Liu and Loyal are now involved with analysis of the 2011 (2012) 7 (8) TeV data. Bocci is a co-convener of the ATLAS Electron/photon Performance Group responsible for all aspects of electron/photon measurements from the ATLAS detector.

We have completed analysis of the first 1.0 fb^{-1} of the 2011 ATLAS data. Goshaw was one of the editors of this Letter that has recently been released for publication [3]. In this study, events triggered on high E_T electrons and muons are used to select the production processes $p + p \rightarrow l + \nu + \gamma + X$and $p + p \rightarrow l + l + \gamma + X$ where the photons have transverse energy $E_T > 15$ GeV and are isolated by requiring $\Delta R(l - \gamma) > 0.7$. Production cross sections and kinematics are measured and di-boson events $p + p \rightarrow W\gamma$ + X and $p + p \rightarrow Z\gamma$ + X are selected by requiring a photon with $E_T > 60$ GeV. The measurements with high

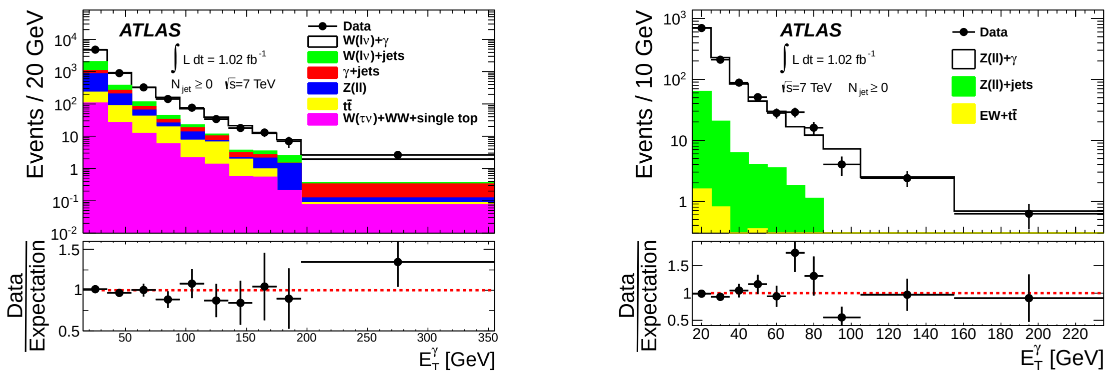

Figure 3: The photon E_T spectrum from Wγ (left) and Zγ events using 1.02 fb^{-1} of 7 TeV pp collisions. The data (points) are compared to the sum of SM predictions plus backgrounds as indicated in the plots.

E_T photons are used to extract limits on anomalous triple gauge-boson couplings.

Our measurements are compared to both leading-order (LO) and next-to-leading order (NLO) SM matrix elements predictions. The LO predictions use ALPGEN (for Wγ) and SHERPA (for Zγ) for the full shower Monte Carlo predictions. We have worked closely with the MCFM authors (J. Campbell, K. Ellis and C. Williams) to learn how best to compare these NLO predictions with our measurements. Two of us (DiClemente and Goshaw) have carried out the calculations used in comparisons to data. We find from our studies that by matching LO matrix elements production with 0,1,2 3,4,5 partons (0,1,2,3 patrons) for Wγ + X (Zγ + X) simulations the SM predictions reproduce well kinematic distributions with the application of a constant k-factor to account for higher order QCD contributions. This is illustrated by the photon E_T distributions in Figures 1 a) for Wγ and 1 b) for Zγ. The jet multiplicity spectrum is also well simulated as shown in Figure 2. The magnitude of higher order QCD corrections are estimated using the NLO parton-level generator MCFM. These NLO SM predictions agree well with our measured cross sections for the exclusive processes $p + p \rightarrow l + \nu + \gamma + X$and $p + p \rightarrow l + l + \gamma + X$ when the system "X" has no central jet with $E_T > 30$ GeV. Table 2 shows a comparison between our measured cross sections and the NLO MCFM predictions. We put limits on anomalous W/Z boson structure in terms of anomalous triple gauge-boson coupling (aTGC) parameters. These are summarized in Table 3. The manuscript describing all these measurements is complete and has been published in Physics Letters B [3].

We continued analysis of Wγ and Zγ production using the 2011 (7 TeV) and 2012 (8 TeV) ATLAS data sets. The full 5 fb^{-1} of data collected in 2011 has now been analyzed. Goshaw was one of the contact editors for this analysis. This analysis required further refinements in comparisons to SM theory predictions as we are now limited by systematic errors over much of the kinematic range of the W/Z boson and photon production. The expertise of Bocci as electron-photon group co-convener was especially important in helping us reduce the dominate systematics from photon detection efficiencies and background corrections. The data were used to put limits on TGCs and the production of techni-mesons $\omega_{TC} \rightarrow$ Zγ and $\rho_{TC} \rightarrow$ Wγ. All these results were collected in one paper and recently published in

Channel	E_{T}^{γ} (GeV)	Cross section exclusive
$pp \to l^{\pm}\nu\gamma$	> 15	3.32 ± 0.10 ± 0.48 pb
(SM Theory)		2.84±0.20 pb
$pp \to l^{\pm}\nu\gamma$	> 60	0.15 ± 0.01 ± 0.02 pb
(SM Theory)		0.134 ± 0.021 pb
$pp \to l^{\pm}\nu\gamma$	> 100	30 ± 6 ± 6 fb
(SM Theory)		34 ± 5 fb
$pp \to l^{+}\ l^{-}\gamma$	> 15	1.05 ± 0.04 ± 0.12 pb
(SM Theory)		1.08 ± 0.04 pb
$pp \to l^{+}\ l^{-}\gamma$	> 60	47 ± 7 ± 4 fb
(SM Theory)		43 ± 4 fb

Table 2: Comparisons of measured cross sections for the $pp \to l^{\pm}\nu\gamma + X$ and $pp \to l^{+}\ l^{-}\gamma + X$ to the SM predictions at NLO as calculated by MCFM

aTGC Parameter	Measured limit
$\Delta\kappa_{\gamma}$	(-0.33,0.37)
λ_{γ}	(-0.060,0.060)
h_3^{γ}	(-0.028,0.027)
h_3^{Z}	(-0.022,0.026)
h_4^{γ}	(-0.00021,0.00021)
h_4^{Z}	(-0.00022,0.00021)

Table 3: The measured 95% CL intervals on the charged ($\Delta\kappa_{\gamma}$, λ_{γ}) and neutral (h_3^{γ}, h_3^{Z}, h_4^{γ}, h_4^{Z}) anomalous couplings.

Phys. Rev. D [4]

Using the high statistics now available with 8 TeV 2012 ATLAS data, we are now extending our Wγ and Zγ studies to include W/Z production with two associated high E_T photons, and a dedicated search for the decay H $\to$ Zγ. Publications on these three topics are planned for by the end of 2013.

4.2 ATLAS management and support activities: Benjamin, Bocci, Goshaw, Liu

Our service work to the ATLAS experiment includes support of the operation of the Transition Radiation Tracker, leadership in improving the precision of electron/photon measurements, and support of various aspects the ATLAS computing infrastructure.

4.2.1 Support of TRT hardware, software and monitoring

We have made various contributions to the support of the Transition Radiation Tracker since its installation in the ATLAS detector. Bocci has played a key role in the commissioning of the TRT. He designed and implemented a track-based alignment algorithm for the TRT [7] and used the cosmic ray data collected after the 2008 LHC accident to assess the performance of the Inner Detector tracking [6]. In the same period he was appointed TRT offline coordinator for a two-year term (2007-2009), an important leadership role carrying the main responsibility of all aspect of the TRT detector software and in particular the coordination of all the activities devoted to the detector readiness for the data taking (i.e. raw data compression, simulation, digitization, calibration, alignment, monitoring and data validation).

Liu and Goshaw have designed and produced a TRT monitoring ntuple that is used

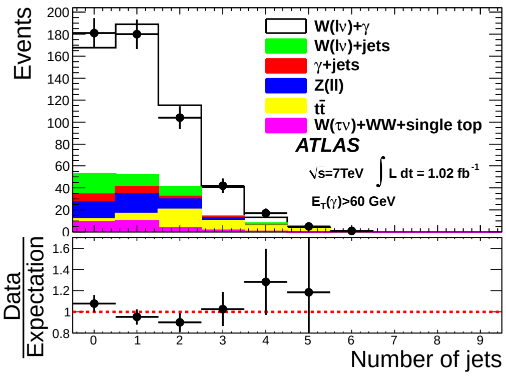

Figure 4: Distribution of jet multiplicity in Wγ + X events with photon E_T greater than 60 GeV.

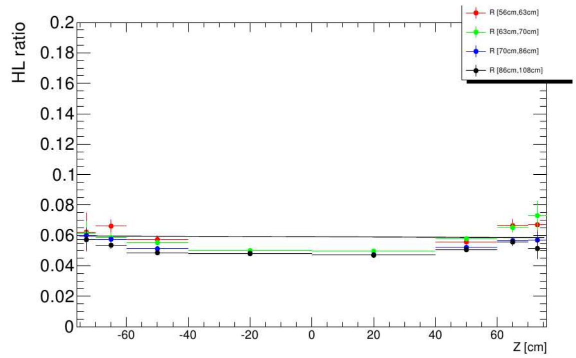

Figure 5: Measurements of high-level hit fraction on tracks in the barrel section of the TRT. This is monitored versus z position along the straws to monitor aging affects as described in the text.

to evaluate changes in TRT performance with time and LHC operating conditions. Average time and position resolutions are recorded in barrel and end-cap straw tube layers and then studied as a function of integrated luminosity, instantaneous luminosity, interactions per crossing, proton bunch spacing, etc. The tool is important for monitorimg small short term drifts in TRT performance so that appropriate action can be taken. In addition Liu (along with Anitioli Romaniouk at CERN) is developing methods for tracking long-term TRT aging. This study is done by projecting tracks into the TRT and measuring the ratio R of high-level hits (used for electron ID) to low-level hits (used for tracking) along the direction of gas flow in the straw tubes. Figure 5 shows an example of the type data that will be monitored for the barrel section of the TRT. Aging effects are not evident in current TRT operation, but this type on monitoring will be valuable to follow trends in long-term TRT performance.

4.2.2 Electron/photon performance: Bocci

The impact of the Duke HEP group in the ATLAS electroweak physics program has been further strengthen since Bocci was appointed (March 2011-October 2013) as co-convener of the Electron/Photon Combined Performance group (egamma CP), one of the most active performance group in ATLAS. In this important role he is responsible for the organization, coordination and supervision of several activities devoted to assure the optimal measurement of e/γ signatures from which several analyses critically depend. In the current ATLAS organization the egamma CP group is responsible for common definitions and measurement of the performance of electrons and photons such that they can be used by the whole collaboration and consistently applied across all ATLAS physics analyses and publications [5]. Because of the strong relevance of those activities for both the ATLAS physics program on searches (i.e. Higgs, SUSY, Exotics sectors) and precision physics (i.e. Standard Model Electroweak sector), in his role as gamma CP Co-convener, Bocci is member of the ATLAS Physics Coordination and reports directly to the Physics Coordinator.

4.2.3 ATLAS Computing and Software: Benjamin

From August 2010 to March 2012, Benjamin was the ATLAS Tier 3 technical coordinator. This role is a natural extension and augmentation of his role as US Tier 3 coordinator. In this role he helped research groups across ATLAS design and setup their local computing and integrated into the ATLAS computing. He also worked with other members of the ATLAS software and computing groups to identify the tools needed for physicists to analyze the data. Through his efforts with the ATLAS data distribution development team, he created simpler and easier to maintain methods and software for delivering ATLAS data to the Tier 3 sites. Benjamin has served as an advocate and liaison between university groups and ATLAS computing on issues of local analysis computing.

4.3 US ATLAS Support Activities

The Duke HEP group has been contributing to the US ATLAS research program in various ways. Goshaw has been Chair of the US ATLAS Institutional Board and Executive Committee for five years. Benjamin is the US ATLAS Tier 3 Manager responsible for support of all US Tier 3 centers. Kotwal and Kruse have served on search committees and review panels. Arce and Kruse are setting up test facilities at Duke and ANL for the upgrade of the silicon strip detector.

4.3.1 US ATLAS Institutional Board Chair: Goshaw

The US ATLAS Institutional Board (IB) deals with general issues of policy affecting the US ATLAS Collaboration. Goshaw was re-elected in January of 2011 to a three-year term as IB Chair. In this role he attempts to strengthen communication between the institutions and the various components of the US ATLAS leadership. IB meetings are held monthly to hear reports from the project managers, to provide input on nominations for ATLAS leadership positions, and to collect feedback on issues affecting the US ATLAS physics program. The IB Chair forms committees that carries out searches and make recommendations for various ATLAS leadership positions: Deputy Operations Manager; M&0 Manager, Physics Support and Computing Manager and Upgrade R&D Manger. The IB Chair also serves as Chair of a newly-formed Executive Committee that consists of the Manager and Deputy, project leaders, and three at-large members elected by the US ATLAS Collaboration. Typical activities are to conduct long range strategic planning, discussion of the budgets for the Operations Program and the review of upcoming presentations from U.S. ATLAS to funding agencies. As IB Chair Goshaw reports at DOE/NSF Reviews and the LHC JOG about general activities of the IB and the manner in which institutions are supported by the US ATLAS Operations Program.

4.3.2 US ATLAS Tier 3 operations management: Benjamin

During 2010 and early 2011, as the US ATLAS institutions began to receive their ARRA funds, Benjamin developed code and instructions for institutions to setup their Tier 3 clusters. They have been extremely helpful (based on surveys of US ATLAS members) in assisting others in setting up their local computing resources. During 2010 as groups were planning their Tier 3 purchases, Benjamin held many phone meetings with US ATLAS institutions aiding them in their design of the Tier 3 clusters. As the 40 US ATLAS institutions have brought their Tier 3 computing clusters online, Benjamin either traveled to the sites to assist (10 such trips) or accessed the clusters remotely. He provided and continues to provide technical support to all of US ATLAS. In 2010 Benjamin became the US ATLAS Tier 3 coordinator. As the Tier 3 coordinator, he is a member of the US ATLAS Task Force charged with developing a plan for replacement of the existing Tier 3 clusters.

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5 Task A - Ashutosh Kotwal (co-PI)

Postdoctoral Associates: Bodhitha Jayatilaka, Shu Li
Graduate Students: Benjamin Cerio, Christopher Pollard, Yu Zeng
Undergraduate Students: Blake Hament, Bernard Liu

5.1 Introduction

This section describes Kotwal's research program within the CDF and ATLAS collaborations. These activities were funded from Task A under the proton accelerator research area. There are three components: measurements of W boson mass and top quark mass at CDF; searches for Higgs and new physics at CDF and ATLAS, and support of the CDF and ATLAS operations and upgrade programs. We worked closely with the Duke research programs directed by Arce, Goshaw and Kruse as there are many topics of common interest in physics analyses and technical support of the ATLAS experiment.

As of the writing of this report, six students participate in our research program. Cerio is a sixth year graduate student on ATLAS who has been studying vector boson fusion $H \to WW$ production in the dilepton channel. He will complete his Ph.D. research on this SM Higgs search based on the full 20 fb^{-1} dataset. Pollard is a fifth year graduate student working on the $t\bar{t}$ resonance search on ATLAS, and will also use the 2012 data for his Ph.D. thesis. Zeng defended his Ph.D. thesis on the W boson mass measurement from 2.2 fb^{-1} of CDF data. The undergraduate students worked on data analysis and ATLAS upgrade. The salaries and travel of the undergraduate students were supported from a Duke University grant independent from this DOE/HEP grant.

Past students and postdocs who worked with Kotwal are well-placed in academia or industry. Postdoc Christopher Hays is now a faculty member at Oxford University working on CDF and ATLAS. Graduate student Heather Gerberich moved to a postdoc position at University of Illinois, Urbana-Champaign. Masters student Joshua Tuttle moved to Synopses, Inc. while masters student Ravi Shekhar enrolled in the Environmental Sciences Ph.D. program at Yale University. Zeng is gainfully employed in the petroleum industry. Recent graduate Siyuan Sun wrote an undergraduate Senior Honors thesis on the ATLAS search for $Z' \to \mu\mu$ and his original contribution was included in the ATLAS publication. He won the Duke Physics Department's Daphne Chang Memorial Award and is now a graduate student at Harvard University. Postdoc Jayatilaka has received Fermilab's highest award for a postdoc, the Tollestrup Award, in 2012 and is now a scientist at Fermilab. He has been replaced by new postdoc Shu Li.

5.2 CDF physics

In this section we describe the recent research conducted by Kotwal's group on CDF.

5.2.1 Precision Physics - the CDF W Mass Analysis

Jayatilaka and Kotwal led the recent analysis of the W boson mass with the unprecedented precision of 19 MeV, the world's best measurement. This measurement (**Phys. Rev. Lett. 108, 151803 (2012)**) was significantly more precise than the previous world average and was featured on the cover of PRL. Jayatilaka is the convener of the W mass group.

Jayatilaka, Kotwal and Zeng, in collaboration with colleagues from Argonne, Oxford, TRIUMF and University College, London performed this measurement of the W boson mass using 2.2 fb^{-1} of CDF data. We achieved self-consistent energy/momentum calibrations with a precision of 0.01%, an improvement by a factor of three over our previous result. We completed an accurate alignment of the COT drift chamber with cosmic rays, using techniques developed by Kotwal. The tracker has been calibrated using $J/\psi \to \mu\mu$ and $\Upsilon \to \mu\mu$ mass fits by Yu Zeng, as part of his Ph.D. thesis work under the supervision of Kotwal. He has made precise measurements of the track energy loss in the silicon detector, the magnetic field non-uniformity and the global deformations of the tracker. Zeng's Ph.D. thesis topic is the measurement of the W boson mass in the muon channel.

Kotwal performed the EM calorimeter calibration by fitting the E_{cal}/p_{track} spectrum of electrons from $W \to e\nu$ decays. We have performed detailed studies of the calorimeter using a full GEANT4 simulation, to understand the effects of longitudinal leakage and uninstrumented material. This is the first time the EM calorimeter has been understood at this level of detail, and these studies have been published in **Nucl. Instr. Meth. A 729, 25 (2013)**. We have also developed an improved model of the hadronic recoil using the high-statistics W and Z boson data. Jayatilaka did detailed studies of the effects of higher order QED corrections using the PHOTOS and HORACE programs, as well as detailed studies of various backgrounds in both channels. Zeng developed a neural network discriminant to measure the jet background in the $W \to \mu\nu$ data, and estimated the PDF uncertainties on the W boson mass.

In this analysis a powerful cross-check was demonstrated by independently measuring the Z boson mass in the dimuon and dielectron channels. For the latter, the mass was measured separately using the calorimeter clusters and the tracks. This is the first time this cross-check has been published at this level of precision and detail. These cross-checks show consistency with the world-average Z boson mass and add confidence in our result. Jayatilaka, Hays and Kotwal are now writing a PRD article describing in detail the techniques used to make this measurement.

Prior to this analysis, Kotwal led the previous CDF W mass measurement with 200 pb^{-1} of data that was published in **Phys. Rev. Lett. 99, 151801 (2007)** and **Phys. Rev. D 77, 112001 (2008)**, with a precision of 48 MeV, which also was the best single measurement at the time. Kotwal co-authored a review article on the measurement of the W boson mass at the Tevatron, which is published in **Ann. Rev. Nucl. Part. Sci. 58 (2008)**. He has been invited to write another review article in this journal.

5.2.2 Top quark mass measurement in the dilepton channel at CDF

The top quark mass m_t is another key parameter of the Standard Model. Shekhar (Kotwal's past graduate student), Jayatilaka and Kotwal and CDF collaborator Daniel Whiteson (UC Irvine) have measured the top quark mass from dilepton events using a per-event likelihood technique. Our analysis of 2 fb^{-1} of CDF Run II data, using an amalgamation of matrix-element and "genetically-evolving" neural network techniques, has been published in **Phys. Rev. Lett. 102, 152001 (2009)**. The use of the evolutionary neural network for event selection resulted in a 20% improvement in the statistical uncertainty, and was the first published use of this technique in HEP. The result was $m_t = 171.2 \pm 2.7(\text{stat}) \pm 2.9(\text{syst})$ GeV, the world's best measurement of the top quark mass in the dilepton channel. This paper followed our two previous publications of the top quark mass in the dilepton channel, also using per-event likelihoods computed using the SM matrix elements.

5.2.3 Higgs boson search in the ZH channel at CDF

At 125 GeV, the decay of the SM Higgs is dominated by the process $H \to b\bar{b}$, which is important because it tests the Higgs coupling to fermions in a manner complementary to the LHC. Shekhar, Jayatilaka, and Kotwal have pursued searches in the $ZH \rightarrow l^+l^-b\bar{b}$ channel by calculating per-event likelihoods constructed from SM matrix elements for the signal and background processes. As with the top mass measurement, we exploit the full kinematic information in the data events, including all momentum and angular correlations such as those due to the Higgs being a scalar particle. This analysis pioneered the use of the per-event likelihood technique using SM matrix-element calculations in this channel. This measurement, Shekhar's thesis topic (supervised by Kotwal), was completed using 2.7 fb^{-1} of data and published in **Phys. Rev. D 80, 071101 (R) (2009)**. We then worked with collaborators from Wayne State University to combine this method with the artificial neural network method. The combination improved the sensitivity by 20% and was published in **Phys. Rev. Lett 105, 251802 (2010)** based on 4.1 fb^{-1} of data.

As co-leader of the $ZH \rightarrow l^+l^-b\bar{b}$ working group at CDF, Jayatilaka has coordinated subsequent analyses in this channel. Using 7.9 fb^{-1} of data, Jayatilaka and his collaborators considerably increased the acceptance of Z bosons candidate events by adopting a neural network-based selection in both muon and electron decay channels. These selection improvements as well as refinements in the final discriminant improved the sensitivity by another $\sim 20\%$, and has been published in **Phys. Lett. B 715, 98 (2012)**. This analysis was the thesis analysis for students at both The Ohio State University and Yale University.

Using the final CDF dataset of 9.5 fb^{-1}, Jayatilaka's group has included further improvements, including the advanced b-tagger HOBIT. This result has been published in **Phys. Rev. Lett.**.

5.2.4 Search for 4$^{\text{th}}$ generation neutrino at CDF

Jayatilaka and collaborators at UC Irvine have performed a search for 4th generation neutrinos produced in conjunction with a pair of Z bosons. In 4th generation extensions to the SM, the lightest 4th generation particle could be a neutrino that is a mixture of Dirac and Majorana states. The search, performed with 4.1 fb^{-1} of CDF data for a range of possible mass eigenstates, establishes the first direct experimental limits on such 4th generation neutrinos. This analysis has been published as **Phys. Rev. D 85, 011104(R) (2012)**.

5.2.5 CDF search for sneutrino, Z' boson and graviton in the dimuon channel

Kotwal led the high-mass dimuon resonance search at CDF using 2 fb^{-1} of data. He pioneered the use of fully simulated lineshapes (templates) for signal and background to scan the dimuon mass distribution to search for resonances. He also invented a technique to automatically account for the momentum-dependence of the tracking resolution. These results (**Phys. Rev. Lett. 102, 091805 (2009)**) were the world's best limits in some models.

Subsequently, Kotwal collaborated with colleagues from UC Irvine and NYU to use a per-event likelihood discriminant based on SM matrix elements for this search. This method provided an improvement of 20% in sensitivity and again produced some of the world's most stringent mass limits on supersymmetric neutrinos, Z' bosons and Randall-Sundrum Gravitons (**Phys. Rev. Lett. 106, 121801 (2011)**).

Kotwal has co-authored a review article on new techniques in high-mass resonance searches in **Mod. Phys. Lett. A24, 2387 (2009)**.

5.3 ATLAS physics

Kotwal initiated ATLAS physics analyses in three areas at Duke: SM Higgs boson search, heavy dilepton resonance search, and $t\bar{t}$ resonance search.

5.3.1 Search for SM Higgs boson in the WW channel at ATLAS

Kotwal and collaborators from TRIUMF, Simon Fraser, Oxford and Illinois pioneered the use of the matrix-element technique in the Higgs search at ATLAS. We have confirmed the $H \to WW$ signal that has also been observed with other methods and validated its significance. These calculations are quite CPU-intensive and make excellent use of the Duke Tier3 computer cluster that was funded by the ARRA grant and is shared by the HEP group.

Another challenge in the Higgs search is to prove the existence of the vector-boson fusion (VBF) process $q\bar{q} \to q\bar{q}H \to WW + jj$. This is a very important process because both the Higgs boson production and decay vertices depend only on the HWW coupling, allowing its definitive measurement independent of other Higgs couplings. The VBF process has a much smaller cross section compared to the $gg \to H \to WW$ process, requiring the development of special techniques and optimized selections for its observation. Benjamin Cerio's thesis topic (supervised by Kotwal) is the search for the SM Higgs boson in the vector boson fusion channel $H \to WW \to l\nu l\nu$ using boosted decision tree techniques to use the full kinematic information of each candidate event in the optimal way. This work is in collaboration with TRIUMF, Simon Fraser and UIUC.

5.3.2 Search for Z' bosons, RS gravitons and techni-particles at ATLAS

Kotwal has been the co-editor for the first three ATLAS publications on massive dilepton resonances, using datasets corresponding to 40 pb^{-1} (**Phys. Lett. B 700, 163 (2011)**), 1 fb^{-1} (**Phys. Rev. Lett. 107, 272002 (2011)**) and the $\sim$5 fb^{-1} dataset of 2011, respectively. Kotwal brought his technique based on templates from CDF to ATLAS where it has become the standard search method. His techniques of incorporating interference between Drell-Yan and the new physics have been used in the latest result.

As co-editor, Kotwal has written the bulk of the documentation in the muon channel as well as co-authored and defended the publications in the internal and external review process. These publications have reported on limits in a wide range of models, ranging from new gauge bosons in Grand-Unified Theories, Randall-Sundrum extra-dimensional gravitons, Z^* bosons with tensor couplings, Kaluza-Klein excitations of Z/γ and techni-bosons. Kotwal worked with the ATLAS group working on high-mass dimuons to resolve a number of physics issues related to high-p_T muons. We also benefited from discussions with Duke colleagues regarding the selection of high-p_T leptons.

5.3.3 Search for $t\bar{t}$ resonances at ATLAS

Chris Pollard's thesis topic (supervised by Kotwal) is the search for strongly-produced (e.g. Kaluza-Klein gluons) and weakly-produced (e.g. Z') bosons decaying to a pair of top-antitop quarks. Top quarks may offer a special window on new physics due to their large mass. In a number of new physics models of Z' bosons and Randall-Sundrum Gravitons, the decay channel to the heavy top quark dominates. Pollard and Kotwal in collaboration with TRIUMF, Simon Fraser University and Oxford are leaders in the ATLAS search for $t\bar{t}$ resonances. Results with 2 fb^{-1} has been published (**arXiv:1205.5371**). Pollard is re-optimizing the electron selection criteria for higher-mass resonances such that the efficiency does not reduce at higher boost when the electron is proximate to the b-jet. This work is done in close contact with the top quark research of Arce and Kruse.

5.4 CDF Service

Jayatilaka served as the Detector Operations Manager in 2011. This position carried a high level of responsibility for CDF. He was responsible for the day-to-day operation of the entire CDF detector, the coordination of the shift crew and collision hall access, and the immediate response to any problem with the detector or the data acquisition system. As Operations Manager, Bodhitha was on-call 24 hours a day. He gave weekly operations reports to the experiment and to the Fermilab experimental community at the All-Experimenters Meeting.

In 2007, Jayatilaka served as the Calibration Coordinator for CDF. In this role he was responsible for all calibration constants used in the reconstruction of CDF data.

During 2004-2006, Kotwal served as the co-leader of CDF Offline Software and Computing and prior to that, as Simulation Group co-leader and Electroweak Group co-convener.

5.5 ATLAS Service

We worked in the following areas of ATLAS operations and upgrade.

5.5.1 Combined Inner Detector Alignment

The physics performance of ATLAS depends on accurate track reconstruction, for which the global alignment of all ATLAS inner detectors is very important. The global alignment effort was started at Duke by Kotwal and Shekhar (graduate student supervised by Kotwal), by working on the alignment of the pixel, SCT and TRT detectors within the ID Alignment group of ATLAS. This work was done in consultation with Bocci at Duke who worked on TRT alignment. The goal was two-fold: alignment of the three detectors with respect to each other, and the relative alignment of the individual sensors within a given detector.

Shekhar and Kotwal investigated the hit resolutions for the pixel, SCT and TRT that are used to compute the track fit χ^2. We generated time-dependent sets of hit resolutions which are currently being used in official ATLAS data production. Cerio continued this operational task for new data.

Cerio and Kotwal studied in detail various precision effects in the global alignment, such as the beam-spot constraint and the dependence of the alignment on mean track curvature. Our inner detector alignment work builds on Kotwal's significant experience with the CDF drift chamber alignment using cosmic rays and collider tracks. There is also an overlap between this work and our physics interest in searches for Z' bosons using high-p_T muons, and b-tagging highly-boosted top quarks.

5.5.2 Phase 2 Upgrade Physics Studies

Pollard, Li and Kotwal worked on building the physics case for the ATLAS Phase 2 upgrade. Pollard has written the code to perform an analysis in any channel by processing generator-level events through a fast parametric simulation of all observables. Pollard has extended our ongoing analyses of $t\bar{t}$ and dilepton resonances to higher luminosity and beam energy to quantify the improvement in sensitivity under the different upgrade scenarios. Undergraduates Liu and Hament contributed to this effort. Pollard and Li also performed new analyses of vector boson scattering (VBS) to quantify the sensitivity to new TeV-scale resonances in longitudinal W/Z scattering tagged by forward jets. These VBS projections were performed in collaboration with UC Santa Cruz, University College London and Brookhaven. Pollard and Li have presented these studies at the ATLAS Upgrade Week at SLAC, the ATLAS European Strategy Workshop and the Snowmass Workshops.

These sensitivity studies for a "high-luminosity LHC" (Phase 2 upgrade with 3000 fb^{-1} to be collected in the period 2022-2030) and a "high-energy LHC" (a new 33 TeV pp collider) have been documented and submitted to the European Strategy Forum and the Snowmass Proceedings. Kotwal has written the exotics and VBS chapters of these proposals, which underwent a full ATLAS collaboration review.

5.6 Community Service

Kotwal co-convenes and serves as contact person for the Electroweak Physics subgroup of the High Energy Frontier group in the DPF Community Planning Study (Snowmass 2013). In this capacity he organizes studies of precision electroweak measurements, diboson and tri-boson production and vector boson scattering as channels to probe new physics at future lepton and hadron accelerators. This role is synergistic with his work in the ATLAS Upgrade Physics Sub-Committee.

Kotwal is also serving as US ATLAS Physics Advisor. In this capacity he handles physics-related issues for the US ATLAS project, including preparations for the 2015 data analysis and preparing the physics arguments for the 2021 upgrade of ATLAS experiment for high-luminosity running.

In recent years, Kotwal served on the Fermilab Users Executive Committee for 3 years and served as its Chair for one year. He served as the vice-Chair and Chair of the DPF Nominating Committee. He chaired the USATLAS Search Committee for the Physics Support and Computing Manager, and is a member of the USATLAS Upgrade Review Committee and a member of the ATLAS Forward Physics Review Panel. He served as the Electroweak session co-convener at DPF 2009 and the Higgs session co-convener at EPS 2011, organized the HCP Symposium at Duke in 2006 and has served on DOE Review Panels.

5.7 Conference and other presentations

We have given a number of plenary talks and seminars in recent years, which are listed here: *http://www.phy.duke.edu/~kotwal/kotwalTalksFile.pdf*

6 Task A - Mark Kruse (co-PI)

Senior Staff: Doug Benjamin
Graduate Students: Kevin Finelli, Chen Zhou
Undergrads: Francesco Agosti, Stefan Cafaro, Alejandro Cortese, Ryan Stribley

6.1 Overview of personnel and research activities

This report describes the research program directed by Kruse over the past three years. Undergraduate students play a large role in this program and are supported by various other sources independent of the Duke DOE HEP grant. Current Duke graduate students are Finelli and Zhou. Zhou is a third year grad student who won an Argonne Fellowship in 2012 which fully supported him for six months until January 2013. Finelli is a fourth year student who will defend his thesis on our simultaneous measurement of standard model cross sections (section 6.3.1) in August 2013, and will take up a postdoctoral fellowship at the University of Sydney, Australia, starting October 1, 2013. In addition to the personnel listed above, Kruse, as a "partner investigator" of the Australian Research Council (ARC) Centre of Excellence in Particle Physics, based in Melbourne, mentors a postdoc from the University of Melbourne, Antonio Limosani, who is fully supported by an ARC grant. This has helped Kruse carry out some of the activities listed in this section.

In May 2012 Kruse was appointed to the endowed Fuchsberg-Levine Family chair, "which recognizes Duke professors with outstanding records in both research and undergraduate teaching". In addition, Kruse is the US ATLAS Outreach and Education Coordinator, and the US Transition Radiation Tracker level 2 manager.

This program is divided into four main sections (students in bold):

- Transition Radiation Tracker (TRT) service activities: **Finelli, Stribley**, Kruse
- Ongoing ATLAS analyses: **Finelli, Agosti**, Kruse, Limosani, Benjamin
- Ongoing CDF analyses: **Zhou**, Kruse, Limosani
- ATLAS upgrade activities: **Zhou, Cafaro**, Kruse, Benjamin

We worked closely with the research programs directed by Arce, Goshaw, and Kotwal given several areas of common interest and required technical support. In addition, we include here a section on Benjamin's Duke computing activities which benefited all PI's on the Duke DOE HEP grant.

6.2 ATLAS TRT performance activities

Kruse initated at Duke a program of TRT performance related studies, and over the last few years has supervised several personnel all of whom have played an important role in the overall TRT software effort. Beginning in 2006 with Bocci and Wall we made integral contributions to the TRT straw efficiency studies and the TRT alignment. This effort was extended by Klinkby, who lead several efforts including TRT simulation and digitization, high-threshold tuning to data, and studies of TRT shadow tracks, which also involved Duke students. Both Bocci and Klinkby have been conveners of the TRT software group. We continue to involve students in these activities who have maintained a significant Duke impact in the TRT software group. Subsection 6.2.1 highlights the most recent work of Kruse's graduate student Kevin Finelli.

6.2.1 TRT Particle Identification

As the instantaneous luminosity of the LHC increases, the additional interactions per bunch crossing will be manifested as additional primary vertices along the beamline in a physics event. This effect is known as 'pile-up,' and it has significant consequences for physics at ATLAS. The most salient effect of increased pile-up will be a rise in detector occupancy as a larger number of tracks fill the detector. There may be other, more subtle effects that we must study. Finelli spearheaded the study of particle identification performance of the TRT, which is used to distinguish electron tracks from hadron tracks based on their emitted transition radiation. This emission is embodied in the 'high-threshold (HT) fraction' of TRT hits on a reconstructed track. Finelli also investigated the TRT's particle ID performance under high-pileup conditions to see whether its discriminating power will be affected. These are ongoing studies which will be important for the TRT performance in the high-luminosity environment expected after the shutdown (LS1).

Building on the results from 2010/2011 (ATLAS note ATLAS-CONF-2011-128), we have looked for systematic effects of pile-up as measured by the number of reconstructed primary vertices in an event. Preliminary results of studying the high-threshold fraction and time-over-threshold as a function of pile-up shows a very evident effect due to pile-up. We are now starting to involve a Duke undergrad (Stribley) in these studies as his honors thesis project.

6.2.2 TRT level 2 manager

Beginning June 2013, Kruse started a 2-year term as the US TRT level 2 manager, overseeing and coordinating US participation in the TRT project and managing the US TRT budget and associated personnel.

6.3 ATLAS analyses

6.3.1 Top physics: a global analysis technique using dilepton final states

Final states involving a high-P_T electron and muon are relatively rare in the standard model, the main processes being $t\bar{t} \to W^+ b\, W^- \bar{b} \to e^\pm \mu^\mp \nu\bar{\nu} b\bar{b}$, $WW \to e^\pm \mu^\mp \nu\bar{\nu}$, and $Z \to \tau\tau \to e^\pm \mu^\mp \nu_e \nu_\mu \nu_\tau \nu_\tau$. These processes are nicely separated in a phase space defined by missing transverse energy ($\not{E}_T$) and jet multiplicity (N_{jet}), as shown pictorially in Figure 6.

During Run 2 of CDF, Kruse conceived a likelihood technique to simultaneously extract the cross sections of the three main $e\mu$ processes in the $\not{E}_T$-vs-N_{jet} phase space, and thereby provide a more global test of the standard model (in this final state) than afforded by any dedicated cross section measurement. This technique was published by Kruse, his former graduate student Sebastian Carron (now a staff scientist at SLAC), his former postdoc Mircea Coca, and Benjamin (Phys. Rev. D78, 012003 (2008)). We select events with a high-P_T electron and muon (of opposite charge) and make no other requirements on the event. Then we fit the $e\mu$ data in the $\not{E}_T$-vs-N_{jet} phase space to expected templates of the signal and

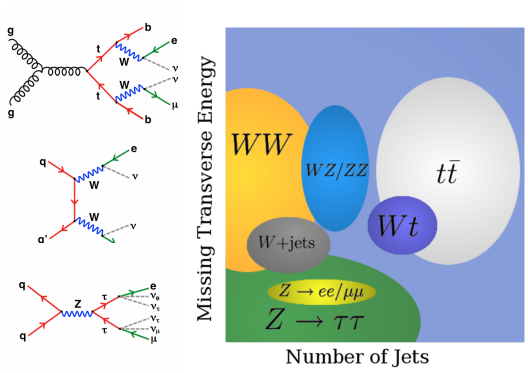


Figure 6: Summary of $e\mu$ final state processes in a phase space that we consider for simultaneously extracting the production cross sections of the three main contributions, $t\bar{t}$, WW, and $Z \to \tau\tau$, which are our "signal" processes. Other contributions are also shown which we consider as our backgrounds.

background processes (derived from Monte-Carlo) using a maximum likelihood function, $\mathcal{L}$, which to first order is a product of Poission probabilities in each (N_{jet}, $\not{E}_T$) bin comparing the observed to expected number of events in each bin. The best fit of the signal template normalizations are used to derive the cross sections of the signal processes. The likelihood value can be used to derive a probability that the data is consistent with SM expectations.

Over the last two or three years, we have been developing this technique for ATLAS. The technique from CDF was coined "AIDA" (An Inclusive Dilepton Analysis), a term that now persists on ATLAS as well. The 2011/2012 version of the analysis has mainly involved Duke (Finelli, Kruse, Benjamin) and the Australian Universities of Melbourne (Antonio Limosani) and Sydney (Andrea Bangert, Aldo Saavedra). The involvement of Melbourne and Sydney is the result of Kruse's involvement with the Australian Research Council Centre of Excellence in Particle Physics (CoEPP), which comprises Australian Universities as the member institutions and a handful of partner investigators (of which Kruse is one).

This small group (by ATLAS standards) have assumed responsibility for all aspects of this analysis, which has involved many detailed studies and tasks, including an understanding of all processes in the considered phase space, estimates of all systematic effects (including those of template shapes), various cross-checks with other analyses, generation and validation of Monte-Carlo samples, development of the likelihood fitting code (originally written by Kruse and Carron for the CDF analysis) and many studies suggested by the ATLAS top and Standard Model physics groups for validating the technique and results.

Our method simultaneously extracts the $t\bar{t}$, WW and $Z \to \tau\tau$ cross sections. As such we present our analysis in the ATLAS Standard Model group, in addition to the top physics group. The results are competitive with the individual dedicated measurements and are consistent with theoretical predications. Figure 7 shows the $\not{E}_T$ distributions for different N_{jet} values, which represents slices of the AIDA 2-D phase space. Note how the process dominance changes as N_{jet} increases, demonstrating the good separation of the three "signal" processes in this phase space.

Our result (at 7 TeV) the associated documentation has been approved internally by an ATLAS editorial board and is now nearing the end of the physics group approvals. A publication draft is in progress. This is the thesis project of Finelli, who is the only grad student working on this analysis. We are also currently working on various analysis improvements for the 8 TeV version of the analysis.

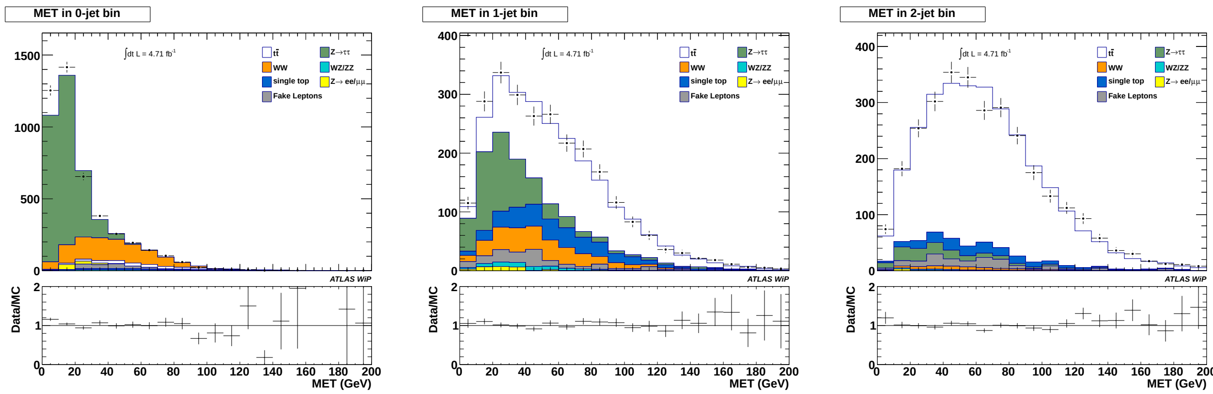


Figure 7: Missing transverse energy for various jet multiplicities, $N_{jet} = 0, 1, 2$ from left to right.

6.3.2 Search for SUSY using trilepton events

As part of Chen Zhou's Argonne fellowship, we worked with collaborators from ANL and Chicago on a search for SUSY in a final state involving 3 leptons, multiple jets, and missing transverse energy. Zhou was based at ANL until May 2013 and worked most closely with Alexander Paramonov (ANL). The 7 TeV analysis has been approved and is now public (ATLAS-CONF-2012-108). Zhou is now focussing on improvements for the 8 TeV analysis. This will most likely be Zhou's thesis analysis, with his main service task being the phase 2 silicon strip upgrade (see below).

6.3.3 Top Physics group software and data management

The ATLAS event data model (EDM) is constantly evolving to keep up with increased demand. The Top Reconstruction subgroup created the two positions of Top Software co-coordinator, given to Finelli and Simon Head (Birmingham) in December 2011. Responsibilities in this position have mainly focused on the top group's specialized D3PD (derived physics data) format, meeting requests from analyzers and performance experts to ensure a common format is available for all top physics studies and results.

In order to more fully support the AIDA analysis effort within the Duke group and to provide a service to the ATLAS collaboration, Benjamin has worked as the ATLAS Top Physics group DAOD/D3PD production and disk space manager since the beginning of 2011. The ATLAS derived data types DAOD and D3PD are used by ATLAS physicists in their data analysis. This effort dovetailed nicely into the work of Finelli.

6.3.4 Search for Anomalously Charged Particles (ACPs)

We used our experience with the operation and performance of the TRT in a search for long-lived particles that have multiple or fractional charges. There are several new physics scenarios which predict such particles. This search used the ionization signatures in the TRT (in combination with the pixel detectors and liquid Argon (LAr) calorimeters) to discriminate particles with multiple or fractional charges. This effort was started by Kruse, Finelli, and Klinkby (former postdoc). It then involved Kruse and Alejandro Cortese, who graduated in

May 2012 and is now a physics graduate student at Cornell. Cortese's undergraduate thesis details the method we developed for this search.

We (Cortese, Kruse) developed a Fisher discriminant technique to search for ACPs in the ATLAS data. We worked most closely with Tim Nelson's group at SLAC, who were looking at other aspects of this search, most notably tracking efficiency studies and the investigation of ways to trigger on the physics of interest. The technique holds promise for future searches.

6.4 Ongoing CDF analyses

The following summarizes work by Kruse, Zhou (grad student), and Limosani (Duke visitor from University of Melbourne working with Kruse) over the last couple of years.

6.4.1 Higgs Boson searches

We (Kruse, Limosani) have been active in Higgs searches at CDF over the last several years.

- Kruse's term of co-convening the CDF Higgs Discovery Group ended in 2009. This resulted in the first direct Higgs boson exclusion at a hadron collider, based on the $H \to WW$ search. Kruse and his former grad student, Dean Hidas, conceived and implemented many innovations to improve the sensitivity of this search channel. This led to publications with Kruse, Hidas and Benjamin as primary authors: Phys. Rev. Lett. 104, 061803 (2010); Phys. Rev. Lett. 104, 061802 (2010); Phys. Rev. Lett. 102, 021802 (2009); Phys. Rev. Lett. 97, 081802 (2006), in addition to a measurement of the WW cross-section (Kruse, Hidas): Phys. Rev. Lett. 104, 201801 (2010).
- Limosani has led the CDF $H \to ZZ$ analysis (with Matteo Bauce (Padova)) in the fully leptonic decay channel. A paper has been submitted for publication in PRD.

6.4.2 Upsilon production in association with a vector boson

We (Kruse, Limosani, Zhou) initiated a new analysis of run 2 CDF data – a search for $\Upsilon + W/Z$ production. Associated production of Υ's and weak gauge bosons (W, Z) is predicted to occur at hadron colliders with low cross sections: at the Tevatron $\sigma(p\bar{p} \to W^{\pm} + \Upsilon) \approx 0.45\,\text{pb}$ and $\sigma(p\bar{p} \to Z^{0} + \Upsilon) \approx 0.15\,\text{pb}$ (Phys.Rev. D60 (1999) 091501). These processes have not to date been observed. Searching for $\Upsilon + W/Z$ production also provides opportunties for new physics (our original motivation), such as charged Higgs searches via $H^{\pm} \to W^{\pm} + \Upsilon$. The Monte-Carlo for the signal was generated using Madgraph, for which one of the Madgraph authors has helped us incorporate the theoretical long-range matrix elements (LRMEs) for the various Υ states. Preliminary results are being presented through the CDF B physics group, and have now started the review process which will lead to a publication.

6.5 ATLAS upgrade activities

We (Arce, Benjamin, Kruse) are actively participating in the phase 2 ATLAS silicon upgrade project, building on extensive CDF silicon detector experience.

Grants in 2010 and 2011 from the Lord Foundation (Arce, Benjamin, and Kruse as PI's) established a module test-stand at Duke based on a custom high-speed I/O (HSIO) board and interface electronics produced by SLAC. In setting up this infrastructure at Duke we collaborated with D. Lynn of BNL. These funds also supported engineering undergraduate students, who are working with us to implement an efficient and thorough testing paradigm using existing detector front-end electronics prototypes, a task involving software and firmware programming. Figure 8 shows the HSIO system working at Duke, which we are continuing to develop.

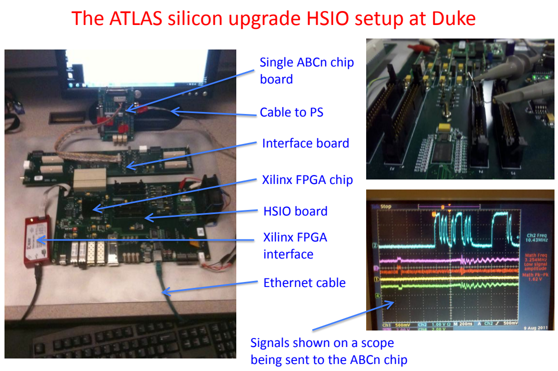


Figure 8: The HSIO setup at Duke to test next generation silicon sensor readout chips. The plan is to evolve this into a module and readout chip testing facility.

6.6 Duke University Tier 3 support

Benjamin has a long history of supporting research computing for the Duke HEP group, both on CDF and ATLAS. He designed, and along with Physics IT staff, assembled the Tier 3 cluster. He is responsible for the installation and maintenance of experiment specific software and computing services located on the cluster. By levering his efforts in ATLAS and US ATLAS, he is able to bring enhancements to Duke that aid the students, faculty and postdocs. He also assisted students in learning how to use ATLAS software and navigate ATLAS computing.

6.7 Conference Talks and Publications

A list of conference talks, public talks, publications, and other activities for Kruse is available at: *http://www.phy.duke.edu/ mkruse/cv_kruse_may2013.pdf*

7 Task A and M - Seog Oh (co-PI)

SECTION 7 (Task A, Task M)

7.1. INTRODUCTION

This section describes the work carried out by **Seog Oh and Chiho Wang** during last seven months**.** We are continuing CDF and ATLAS data analysis and Mu2e straw tracker R&D. The main work for CDF has been finishing up the paper related to the meson production in minimum bias events and Ks and Λ production in jets. The paper is in circulation in the CDF collaboration and will be submitted to PRD soon. The ATLAS analysis work during this period has been also to study Ks and Λ production in jets using 7 TeV data. As shown later, we find that the production properties of Ks and Λ hadrons depend on the jet energy but are insensitive to the center of mass energy. One interesting finding from this analysis is that the PYTHIA fails to reproduce the data at all. This is unexpected since PYTHIA was tuned using jets from e^+e^- annihilations. This is the first time that the p_T distributions of identified particles in high-E_T jets from hadron-hadron collisions have been measured.

For the Mu2e, the collaboration has made the tracking technology choice early this year, and the straw tracker was chosen as the baseline detector. (The other proposal was a tracker similar to the CDF tracker (COT)). We made a good deal of technical contributions in making the choice. We will describe our ongoing R&D for the Mu2e straw tracker.

7.2. CDF/ATLAS DATA ANALYSIS

One of our analysis contributions in CDF has been the study of resonances (Ks, K*,φ, Λ, Ξ, and Ω) using minimum bias and jet data. There are several goals for the analysis. One is to study the flavor production and compare with fragmentation models, such as PYTHIA and HERWIG. Another goal is to compare particle production from minimum-bias and jet events to see if there is a transition at some p_T, above which the particles from jet fragmentation tend to dominate. The third is to provide the data in the region of low p_T where QGP could be produced.

One highlight of the resonance production in the CDF minimum bias events is that their p_T slope of all particles are fairly constant when the p_T distributions (Figure 7.2.1) are fitted with a power law function $((A/(p_0+p_T)^n)$, where A, p_0 and n are parameters. With p_0 fixed at 1.3, the n values for all resonances are about 8 indicating that the physics process of producing particles are independent of quark flavor (u,d and s) and number of quarks in particles.

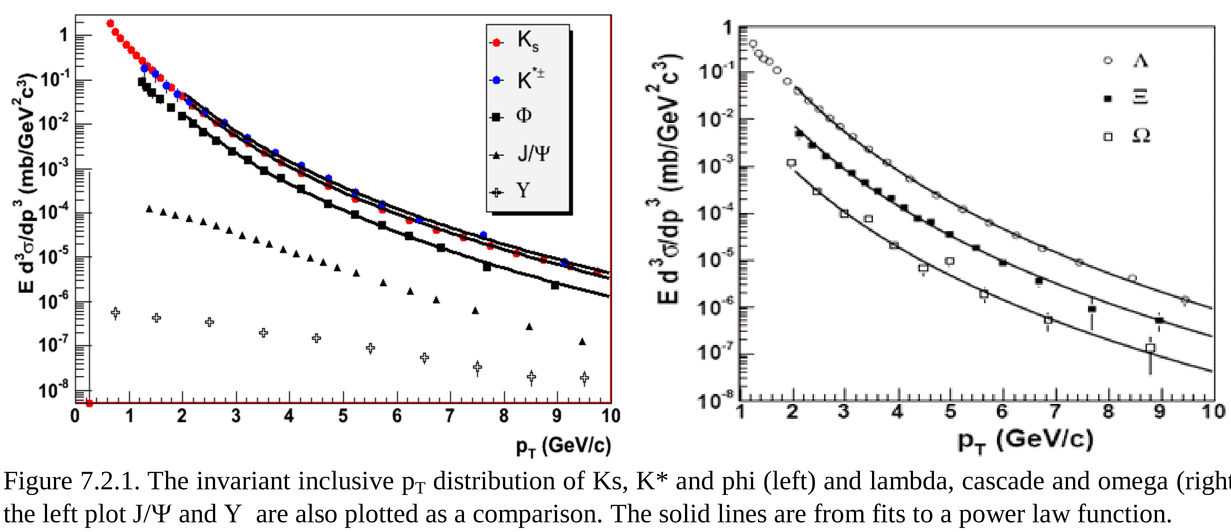


Figure 7.2.1. The invariant inclusive p_T distribution of Ks, K* and phi (left) and lambda, cascade and omega (right). On the left plot J/Ψ and Υ are also plotted as a comparison. The solid lines are from fits to a power law function.

Another interesting finding is in the Λ/Ks ratio as a function of p_T. Figure 7.2.2 shows the ratios from minimum-bias events and jets together. The plot is interesting because the ratios from the minimum bias data and jet data merge as p_T increases. This is consistent with the assumption that the high p_T particles in minimum biased events are likely from soft QCD jets. We also note an enhancement in the ratio near p_T ~2 GeV. The enhancement shows up only in the baryon to meson ratio (not in the ratio of baryon to baryon or meson to meson). This may be an indication of some interesting physics.

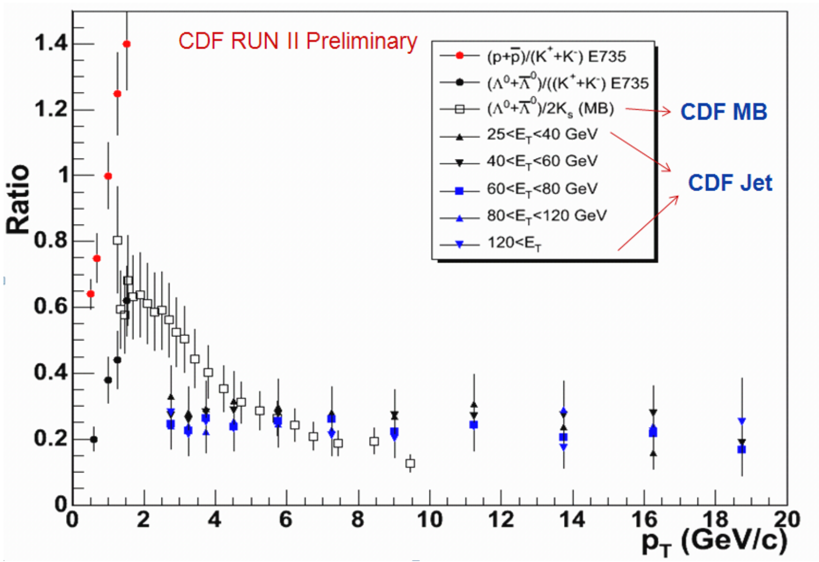
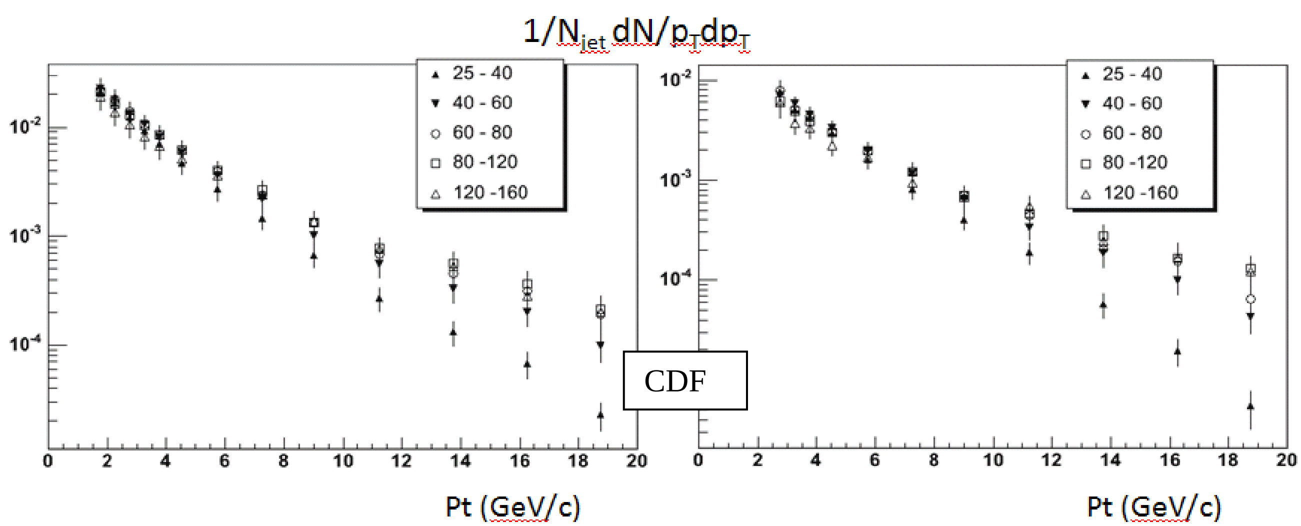


Figure 7.2.2. The ratio of baryon to meson from minimum biased and jet events.

We started a similar analysis using ATLAS data (7 TeV center-of-mass energy). The first task was to move the particle reconstruction program (Ks and Λ) to the ATLAS environment. This was accomplished successfully and we finished a preliminary analysis of Ks and Λ production in jets. The results are quite similar to CDF results. This is not unexpected as jets with 50 GeV E_T, for example, should behave similarly regardless of the center of mass energy from which they are produced.

Figure 7.2.2 below shows the p_T distribution for Ks and Λ hadrons as a function of jet transverse energy. Top two plots are from CDF data and bottom two plots are from ATLAS data. Jets are divided into five E_T ranges. Figure 7.2.3 show the ratios as a function of p_T for the five E_T intervals. The same ratios from PYTHIA events are displaced as well. It is clear that the ratio with PYTHIA data exhibit quite different characteristics. While data show fairly constant ratios for all p_T and E_T ranges, the PYTHIA ratios raise as a function of p_T. This is unexpected since the PYTHIA parameters were adjusted to reproduce the properties of jets from e^+e^- interactions.



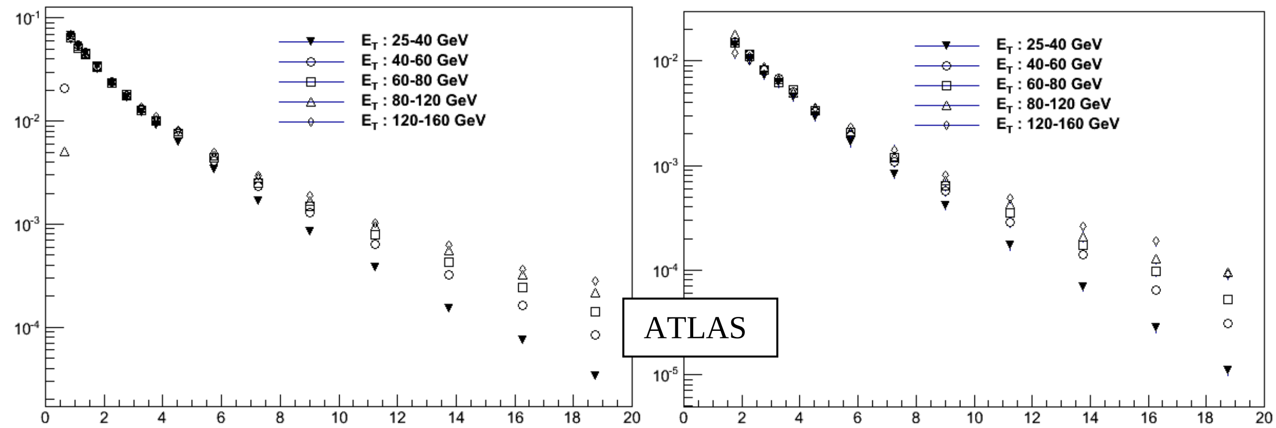


Figure 7.2.2. Top figures are from CDF data and bottom figure are from ATLAS data. Left figures: Ks p_T distributions for five jet E_T intervals. Right figures: Lambda p_T distributions for five jet E_T intervals (25-40, 40-60, 60-80, 80-120 and 120-160 GeV). We note that this is the first time that these particles are studied inside jets.

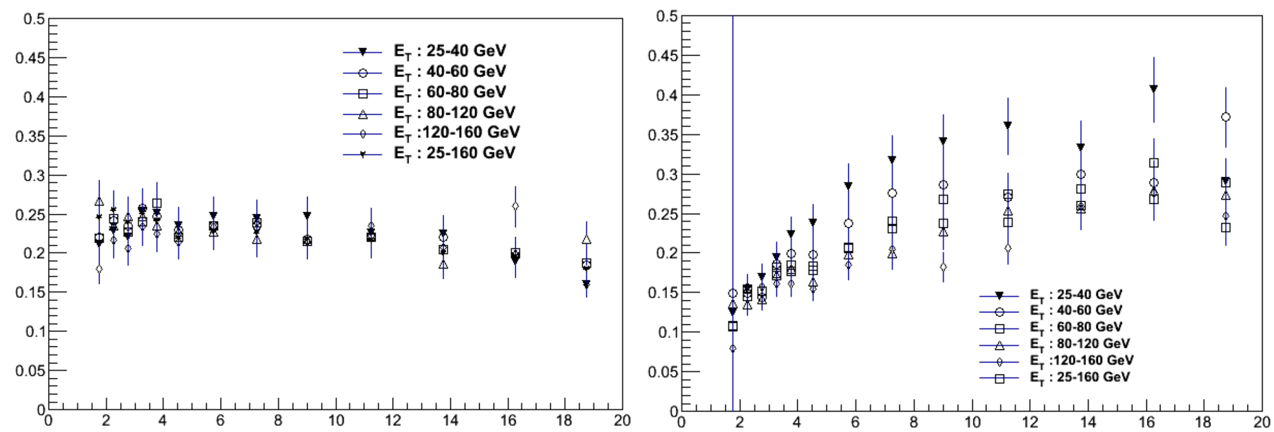


Figure 7.2.3. Left (ATLAS Data): Ks/Λ ratio as a function of p_T for five jet E_T intervals. (25-40, 40-60, 60-80, 80-120 and 120-160 GeV). Right (PYTHIA): The same but with PYTHIA data. The mismatch between two data sets is clear.

7.2. Mu2e

The Mu2e experiment is one of high priority experiments at FNAL. Mu2e received a CD1 approval in the fall of 2012 and we expect CD2 and CD3 approval early next year. The experiment is on schedule with reasonably good funding.

As mentioned in the introduction, the straw tracker was chosen as the baseline tracker in January 2013. We provided several critical technical data for the decision, such as leak rate, straw robustness, straw sagging (as a function of inside pressure and tension) and straw creep rate. Because straws sag, they are under tension to keep them straight. However straws creep under tension (made of Mylar film). As they creep, the tension in straws gets less and the sag increases, which could make the detector inoperable. Figure 7.2.1 shows a picture of our creep-measurement setup and Figure 7.2.2 shows the creep rate for four initial straw tension values, 300, 400, 500 and 600 gram. We have been taking data over a year and plan to continue for another year.

Using the parameters from the fit to the data in Figure 7.2.2, the tension after six years can be estimated, and we found $T/T_0 \sim 0.33$. This implies that straws with initial tension of 600 grams will retain ~200 grams of tension after six years. The value meets the lower limit of the tension requirement, which is also based on out sagging measurement. It is likely that the initial tension would be ~700 grams.

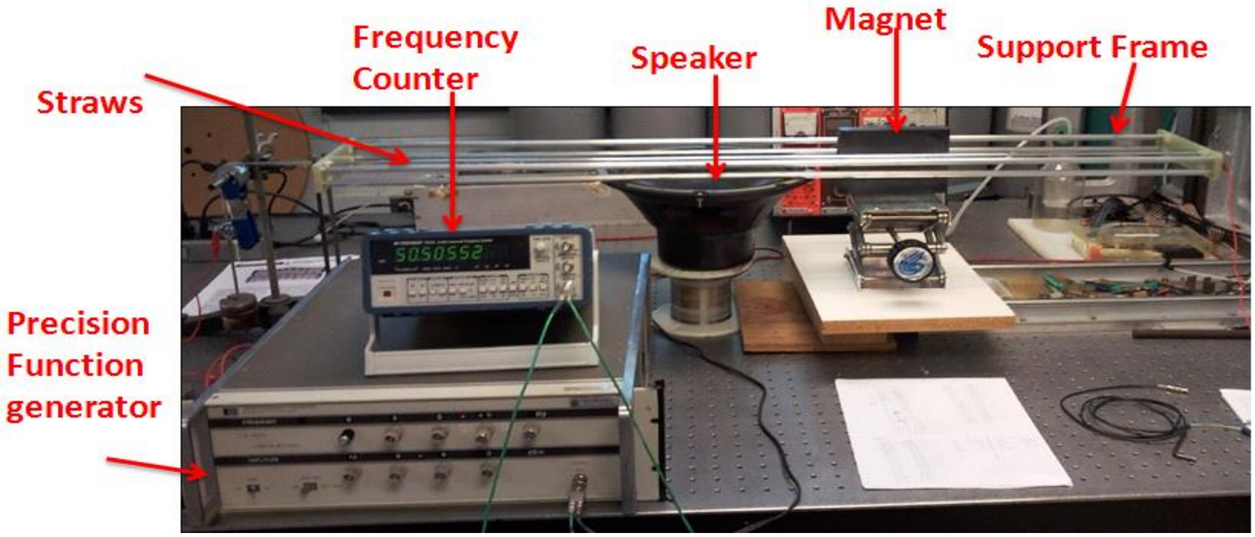


Figure 7.2.1. The setup for the creep rate measurement. The tension is measured by vibrating straws. The resonance frequency can be measured better than 0.05 Hz. The straw length is 120 cm, the length of the longest straws in Mu2e tracker.

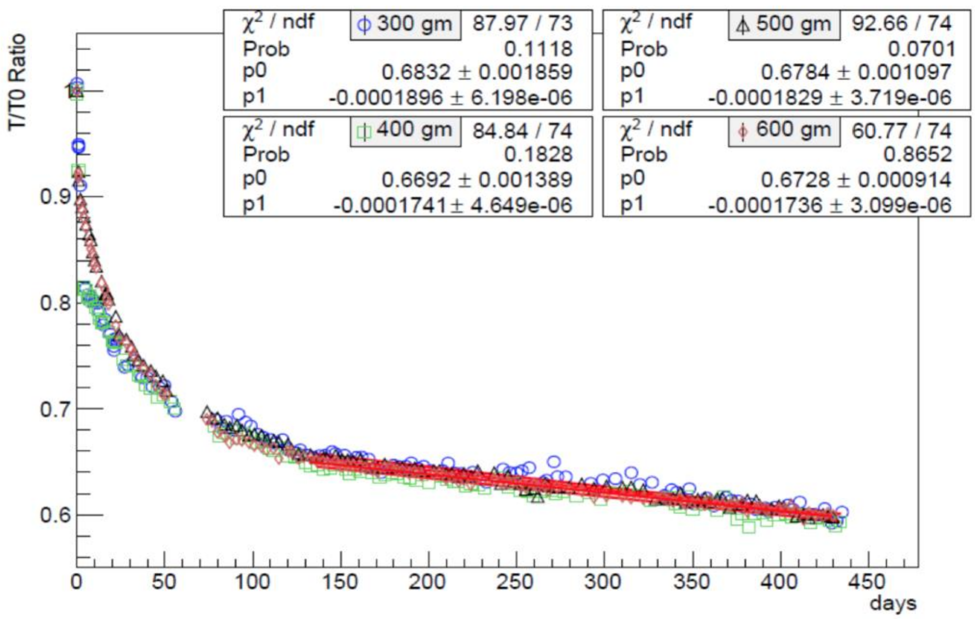


Figure 7.2.2. The creep rate measured over a year. The plotted (T/T_0) is the tension (T) normalized to the initial tension (T_0) as a function of time. There are four plots corresponding to four initial tensions of 300, 400, 500 and 600 grams. The scaling is excellent.

One of our responsibilities is to measure the wire position in three dimensions using an x-ray scanner. There are about ~22000 wires. We have finished a preliminary test using a small prototype scanner and are in the process of constructing a full size prototype. The technique is to move a collimated x-ray beam (50 microns in width and 5 cm in length along the wire direction) across a wire and measure the x-ray transmission rate. Figure 7.2.3 shows a transmission plot as the x-ray beam moves across three different diameter wires separated by 3 cm. There are nice valleys corresponding to the wire locations. Form the fit to the data, we demonstrated that wire position could be measure better than 20 microns. Moreover, by tilting the x-ray source, wire position can be mapped in two dimensions at a given location. We are also exploring a way to measure the straw location by locating two straw walls.

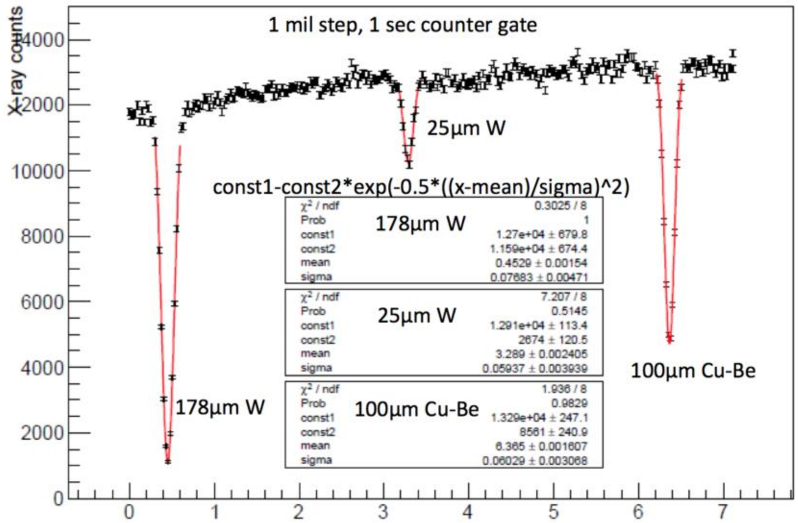


Figure 7.2.3. Data from the prototype x-ray scanner. The y-axis is the number of transmitted x-rays. There are three wires with different diameters, 178, 25 and 100 microns, separated by ~3cm.

With the success of the technique, we are in the process of constructing a full size prototype scanner as shown in Figure 7.2.4. There are two linear slides (x and y movement) with an x-ray tube mounted on one of them. The accuracy of the slider movement is 10 microns. The scanner will be used to measure the first Mu2e straw detector panel prototype to be produced early next year in preparation of CD2 TDR. All parts, including the x-ray tube, are in hands. With this design, we should be able to map all wires in a year.

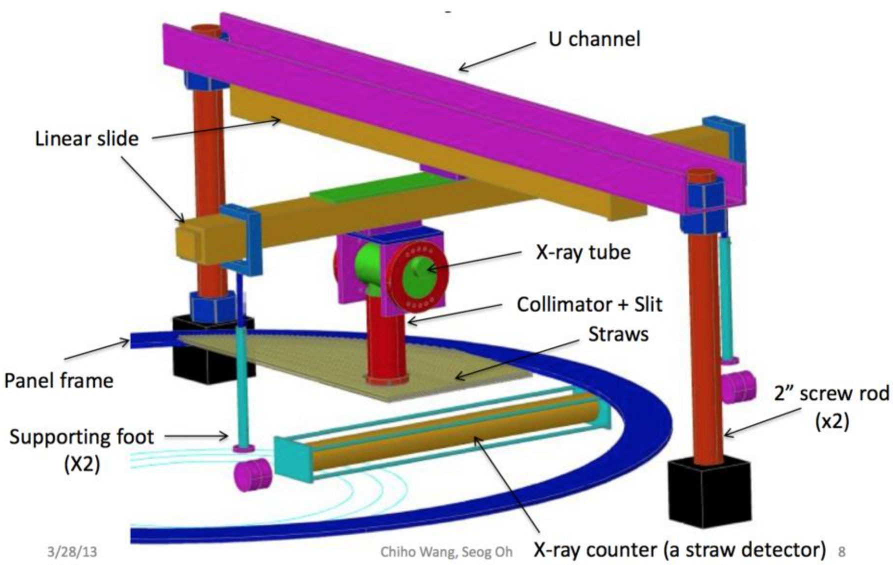


Figure 7.2.4. The Mu2e x-ray scanner (AutoCad drawing). The x-ray tube is mounted on two (x and y) sliders. The U-channel provides the support for the scanner. The collimated x-ray beam moves across straws in 20-micron step. The transmitted x-rays are detected by the detector located below the straws. The x-ray tube can be tilted by +/- 15 degrees to measure the two coordinates. The maximum operating high voltage and current of the x-ray tube is 50 KV and 1 mA respectively. The typical operating voltage and current are 15 KV and 0.2 mA.

Another task we have just started is to incorporate the wire position data to the track reconstruction software. The plan is to measure the coordinate of all anode wires in three dimensions at three locations along wires. Using the data, the wire coordinates in the Mu2e detector will be corrected. The present software does not have this capability and we will modify the software to include the mapping data. Once the modification is implemented, we also plan to study the effect of wire displacement on the track reconstruction efficiency and the momentum resolution, which are critical to reject decay-in-orbit muon background and sort out the signal.

8 Task N: Neutrino Physics Program

8.1 Introduction

The Duke HEP Neutrino Physics program includes the activities of faculty members Kate Scholberg and Chris Walter in the SK (Super-Kamiokande), T2K (Tokai to Kamioka), and LBNE (Long Baseline Neutrino Experiment) collaborations.

In addition to the two faculty members, we currently have two postdoctoral researchers, Tarek Akiri, who started in March 2011 (he graduated from the U. of Paris with a Double Chooz thesis), and Alex Himmel, who joined in July 2011 (he graduated from Caltech with a MINOS thesis, that recently won the FNAL URA award). Postdoc Jennifer Prendki left for a position in the financial industry in December 2010, and last May, Roger Wendell took a permanent faculty position at the University of Tokyo. We have two current graduate students: Taritree Wongjirad, who started in the fall of 2008, and Zepeng Li, who started in 2011. Josh Albert defended his Ph.D. thesis in March 2012, and took a postdoctoral position at Indiana University working on the EXO experiment in July. Jack Fowler is a mechanical engineer contributing primarily to LBNE. In addition, we have a number of undergraduates (and a few high school students) working with us, including four who completed senior theses in the past three years.

	Current	Past Three Years
Faculty	K. Scholberg, C. Walter	
Postdocs	T. Akiri, A. Himmel	J. Prendki, R. Wendell
Grad Students	T. Wongjirad, Z. Li	J. Albert
Undergrads	S. Borhanian, B. Izatt	A. Beck, B. Bellis, F. Beroz*, N. Bodnar, A. Burgmeier, N. Chan*, A. Jones*, N. Kaiser, J. Lozier, N. Sanford, L. Schaefer, A. Tuna* W. Johnson
Engineer	J. Fowler	

Table 4: Task N personnel summary. An asterisk indicates a senior thesis student.

8.2 Progress Report on Work in the Past Three Years

8.2.1 Super-Kamiokande contributions

Duke group members have taken on extensive service responsibilities for SK. In the past three years we have completed many calibration, monitoring, simulation and analysis support tasks for SK IV. The SK ATMPD neutrino data for analysis are generated from the online raw data in a series of steps: first, the data are processed by the "reformatter" and written in a standard format. Next, the offline system applies calibration constants and distributes the data to various "reduction" processes that select neutrino events from cosmic ray muons (approximately 3 Hz) and other background. The atmospheric neutrino events are sorted into "fully-contained" (FC), "partially-contained" (PC) and "upward-going muon" (upmu) subsamples. FC events have outgoing leptons which are contained in the ID; they have light in the ID only. PC events are those with exiting muons, and primarily result from ν_μ: these have light in the ID and OD and are more difficult to separate from cosmic ray background. The PC reduction employs a series of sophisticated cuts to select events with outgoing muons. Upmu events result from neutrinos which interact in the rock and produce muons entering the detector; they can only be separated from cosmic rays by their fitted directions. After reduction, events are fully reconstructed: using PMT time and charge information, the event vertex, energy and particle directions are determined. In the past three-year period we have had responsibilities at nearly every point in the chain from online through reconstruction.

US Group Onsite Maintenance (Wendell): Wendell was resident at Kamioka beginning in fall of 2008, as onsite US group expert, full time (except for six weeks in the summer of 2011). He was responsible for maintenance of power supplies, OD electronics, radon-free air system, and OD PMTs, as well as development of web-based data monitoring.

Reformatter and Offline (Wendell, Scholberg): The reformatter software processes raw data from the online system and passes it to the offline in near-real-time. Wendell had responsibility for maintaining the reformatter over the past three years, and oversaw two Root version upgrades. Scholberg served as Offline Group co-convener.

OD Calibration, Data-Quality Monitoring and Simulation (Scholberg, Wendell, Chan, Jones): Scholberg is responsible for SK IV OD calibration constant generation and bad channel selection. Wendell and Scholberg performed a calibration in 2011 to evaluate OD up/down asymmetry. Wendell had responsibility for SK IV OD Monte Carlo (MC) tuning, which has now attained very high quality.

PC Reduction (Prendki, Wongjirad, Scholberg): Prendki performed PC reduction tasks for the installment of SK IV data in April 2010. Wongjirad has now taken over this task and has performed it for each SK data update since late 2010, producing data and MC files and systematic error estimates. He has developed a new criterion for separating PC stopping and through-going events; these are event classes for which the exiting muon stops in the outer detector, or makes it all the way through. The PC stop/thru separation is useful for improved resolution on L/E for oscillation analysis. Wongjirad's new criterion corrects for position-dependent charge collection in the OD. Wongjirad also developed a new automated PC reduction shift web page.

FC Reconstruction (Akiri, Walter): Walter has continued work on improving and implementing fully-contained reconstruction algorithms. In 2010, he modified and improved the specialized algorithms used to reconstruct τ events for use in the new improved τ analysis. Working with Wendell, Akiri also performed the reconstruction of the τ MC files which were used for the SK IV ATMPD analysis at that time.

Monte Carlo Production (Himmel): In 2010, Himmel took over the production and reconstruction of the ATMPD MC files. We have modified our software, and Himmel redid the work and validation checks for over 500 years of MC for each of SK I through SK IV.

SK IV Energy Scale Calibrations (Albert, Walter): Albert was responsible for using muon decay electrons to make an absolute energy calibration in the Michel electron spectrum energy range, along with checking the new SK IV MC response. He also implemented a real-time process for tracking the response.

Calibration (Akiri): Akiri worked in the SK calibration group to help in exploiting the laser data for determination of black sheet and PMT reflectivity parameters, and performed a full retuning of the parameters.

Oscillation Analysis Tools (Wendell): Wendell was responsible for creation and maintenance of a number of software tools used for ATMPD oscillation analysis, including the systematic error library, a tube connection table interface library, and Root/ntuple libraries. His "Osc3++" tool is now used for a number of analyses in the collaboration and his "Prob3++" three-flavor oscillation probability calculation software has been made publicly available.

Here we briefly survey SK physics analysis work from the past three years.

Three-Flavor Atmospheric Oscillation Analysis: Wendell's three-flavor atmospheric neutrino oscillation thesis analysis was extended to the full SK I, II and III samples and published in PRD [25] (see Fig. 9). Wendell was primary author for this paper, which also included the analysis of ICRR graduate student C. Ishihara.

Neutrino-Antineutrino Analysis: Wendell was also responsible for the SK atmospheric neutrino vs antineutrino analysis, recently published in PRL [21]. Evidence that the survival probabilities P($\nu_\mu \to \nu_\mu$) and P($\bar{\nu}_\mu \to \bar{\nu}_\mu$) are not equal would imply new physics (a recent hint of discrepancy between the measured ν_μ and $\bar{\nu}_\mu$ parameters by MINOS has now gone away). Since SK is insensitive to the sign of the outgoing lepton's charge in a neutrino interaction, it cannot differentiate between ν and $\bar{\nu}$ on an event-by-event basis. Instead, to search for possible differences in their oscillations, SK considers distortions in the $\nu + \bar{\nu}$ spectrum consistent with oscillations governed by two distinct parameter sets. No evidence for a difference is found in the data. The $\bar{\nu}$ fit results are summarized in Fig. 9.

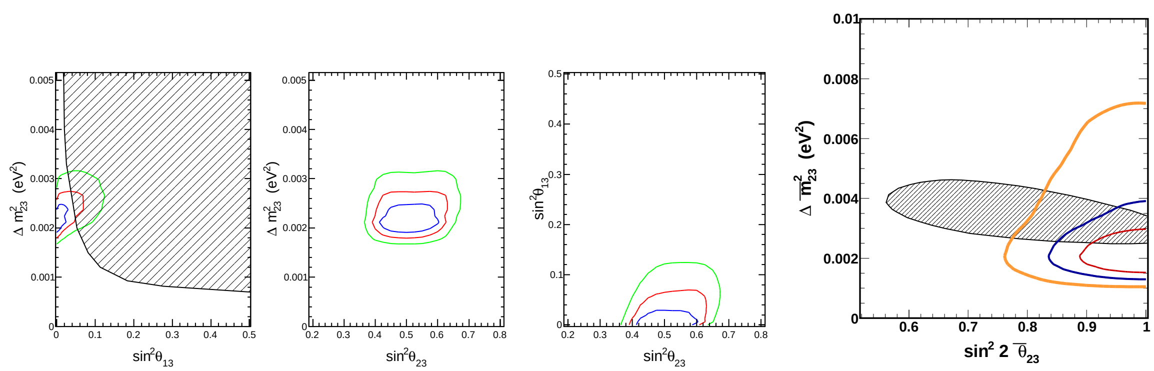


Figure 9: Left three plots: SK I + II + III three-flavor regions [25], for normal hierarchy for $\theta_{13} \neq 0$. Right: Allowed regions (68%, 90%, and 99%) for the $\bar{\nu}$ mixing parameters for the SK I+II+III data set, from [21]. The shaded region is the one originally favored by the MINOS experiment.

Tau Appearance Analysis: If $\nu_\mu \to \nu_\tau$ oscillation is taking place, ν_τ should appear in the atmospheric neutrino flux. Walter performed a search for ν_τ-induced τ lepton events and is a primary co-author of a paper that was published in PRL in 2006. Walter performed an analysis to isolate the ν_τ component of the atmospheric neutrino flux using neural networks (NN) for event selection. Walter has now analyzed the data from SK I, SK II and SK III. He has extended the analysis technique to use multi-dimensional unbinned likelihood fits which use the neural network output of the analysis as fitting variables instead of just cut variables. This approach results in a large increase in sensitivity. The clear separation of the signal from background in this approach can be seen in Fig. 10. This analysis was presented publicly for this first time in December of 2010. With the new precision values of θ_{13} now available from reactor experiments, Walter redid the analyses thus reducing the systematic errors due to three-flavor uncertainties. Approximately 1.4 times the expected number of events were seen and the no-oscillation hypothesis was excluded at the 3.8σ level. This result has now been published in PRL [9]. With the new reduction in systematic errors, Walter also began working to further explore precision three-flavor oscillation physics using this sample.

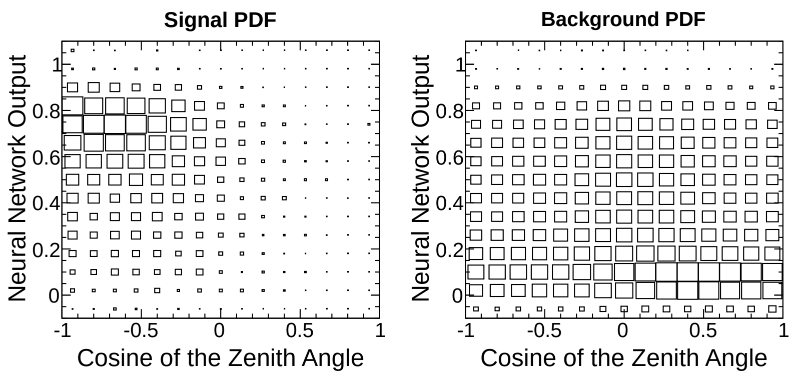


Figure 10: Histograms of the PDFs of both τ signal (left) and atmospheric background (right). The vertical axis is the output of the NN, the horizontal axis the cosine of the event zenith direction. Upward going events are to the left, downward going to the right. The τ signal appears in the upward-going τ-like region.

Lorentz Violation Analysis : Akiri embarked on a new analysis searching for Lorentz-violating effects in the SK atmospheric neutrino data, completing a sensitivity study in early 2013.

Sterile Oscillation Analysis: In 2012, Himmel began an analysis to constrain parameters describing oscillations of sterile neutrinos using SK atmospheric analysis. This analysis was completed and officialized shortly after the period covered by this report.

8.2.2 T2K Contributions

The Duke HEP neutrino group is involved in T2K through work improving and maintaining the SK hardware and software, developing a special sample of OD events, leading several working groups in the experiment, and undertaking the highest-profile analyses.

Current T2K Status: The T2K experiment began running in February 2010 and through the spring of 2011 (Runs 1 and 2), attaining power exceeding the 100 kW level, until operation of the beam was halted by the earthquake in eastern Japan (SK was not affected). The accelerator lab staff and experiment undertook a recovery plan which successfully delivered protons to the target of the T2K beam in December of 2011. Stable data-taking resumed in March of 2012. Throughout this entire period, the SK detector continued running with extremely high stability and uptime.

In June 2011 we presented the first results of the search for non-zero θ_{13} from T2K [16] using ν_e candidate events in SK. We observed six ν_e candidates, with a background expectation of $1.5 \pm 0.3(syst)$. If θ_{13} were zero, the probability to observe six or more candidates is 7×10^{-3}, indicating a 2.5σ significance. These results were the first positive indications of non-zero θ_{13} and heralded the start of a year which saw results from five experiments and culminated in the first precision measurements of the mixing angle. The final T2K results are shown in Fig. 11. This analysis is graduate student Josh Albert's thesis for which he was awarded a Ph.D. in March of 2012. An updated analysis with new data showing the first greater-than-three-sigma significance signal for ν_e appearance was presented at Neutrino 2012 and has now been submitted for publication [7].

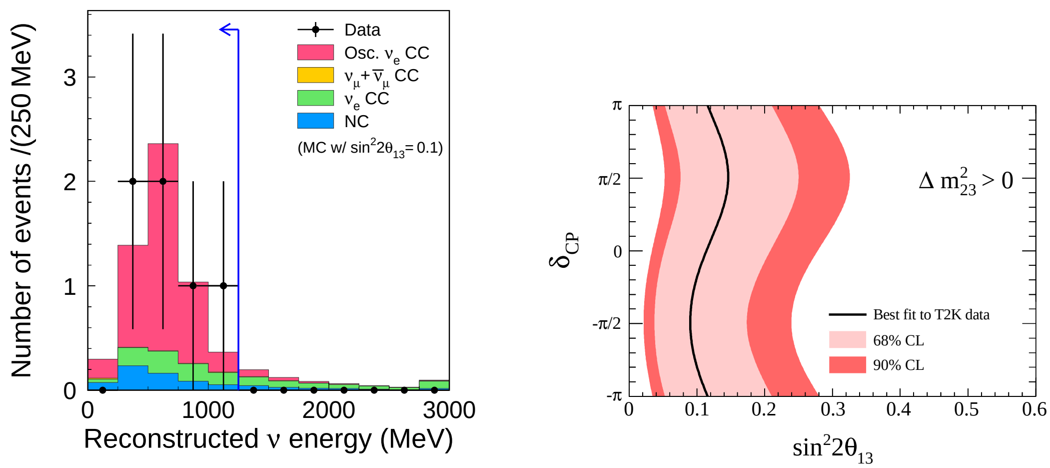


Figure 11: The final ν_e candidate sample after all cuts (left), and inferred allowed region for $\sin^2 2\theta_{13}$ (right) for the normal hierarchy. This analysis was recently published in PRL [16].

Leadership Contributions: Scholberg serves on the T2K Speakers Board for a term starting which started in Fall 2012. Walter is playing a leading role in three groups, as detailed below.

-T2K-SK (Walter): Within T2K, Walter is a co-convener of the T2K-SK group. This is the T2K analysis group which does all SK-related analysis. Some of the responsibilities of this group include calculating systematic errors in the oscillation analysis related to the SK reconstruction algorithms, development of the algorithms used to separate the signal from background in the appearance analysis, and the production of SK MC for T2K.

-SK-LB: (Walter): Within SK, Walter is co-convener of the SK Long-Baseline group. This subgroup is responsible for providing the SK-related software to T2K and for the production of the fully reconstructed SK data during the beam time window. The SK-LB group also makes the T2K-related SK software and data available to T2K collaborators on a set of dedicated computers located at KEK.

-ASGC (Walter): As a member of these groups, Walter also serves in the Analysis Steering Group, which is a steering group of all of the analysis conveners for the experiment. This group meets regularly (including face-to-face meetings in Japan) to drive the scientific policy and roadmap of the experiment. It also serves as the hub of coordination between the very different parts of the experiment and was the vital link between groups in our first ν_e appearance analysis.

The Duke group played an essential role in the analysis presented in our PRL paper [16]. In addition to the roles outlined above, grad student Albert was one of two T2K members who performed the ν_e appearance analysis, integrating the inputs from all of the sub-groups and developing the analysis framework for extracting our physics results. Grad student Wongjirad also played a unique role by carefully calculating expected backgrounds from outside of the SK detector. He is now also one of the main analyzers of the muon disappearance analysis.

Specific T2K service items (beyond SK work) and analysis work are listed below.

T2K Electron Neutrino Appearance Analysis (Albert, Walter): Albert and one other Japanese postdoc (who is now a professor at University of Tokyo) were the primary authors of this paper. Albert played an extremely visible and key role in the collaboration for this result and his work is already being used as the basis of new work by other students and postdocs. He was involved in all analysis aspects, including background classification, optimization and calibration for the SK data. Working with Walter, he optimized the ν_e event selection criteria for current running conditions and also implemented a statistically-rigorous sensitivity calculation which incorporates known systematic errors.

Official Plots (Albert, Scholberg, Walter, Wendell, Wongjirad): As T2K-SK convener, Walter organized the production of all official plots for SK and the ν_e and ν_μ oscillation analyses that are being shown publicly. Albert produced plots for the ν_e analysis, Wongjirad and Scholberg produced plots for studies related to OD events, and Wendell produced plots using the atmospheric neutrino data to check vertex distributions of the T2K sample. Wendell also oversaw the overall study of vertex distributions and also developed a set of future checks to be applied to future data so as to ensure that they were unbiased.

T2K OD Events (Wongjirad, Scholberg): Wongjirad is working with Scholberg on selection of T2K events with light in the OD. These events include ν interactions with final state particles which exit the OD (PC), interact in the OD itself, or enter from the rock. Wongjirad is responsible for the T2K SK OD event reduction, and has developed selection and classification criteria to improve signal to background.

Wongjirad's work has turned out to be especially important for the recent T2K oscillation results: following the unblinding of our dataset, in view of the apparently non-uniform ν_e candidate vertex distribution, he did extensive studies to understand the contamination due to beam events entering the detector from interactions outside of the ID. His OD event sample shows no vertex anomalies, and his contamination MC studies show that background ν_e candidate events in the fiducial volume should be negligible (see Fig. 12). Wongjirad is currently working on improving the rock simulation and evaluating systematics. He is evaluating sensitivity of a ν_μ oscillation analysis incorporating OD events.

MC Sensitivity Studies (Albert, Walter): Using the framework they developed for the ν_e oscillation analysis, working with Walter, Albert produced internal T2K plots projecting expected sensitivities and discovery potentials for various future scenarios.

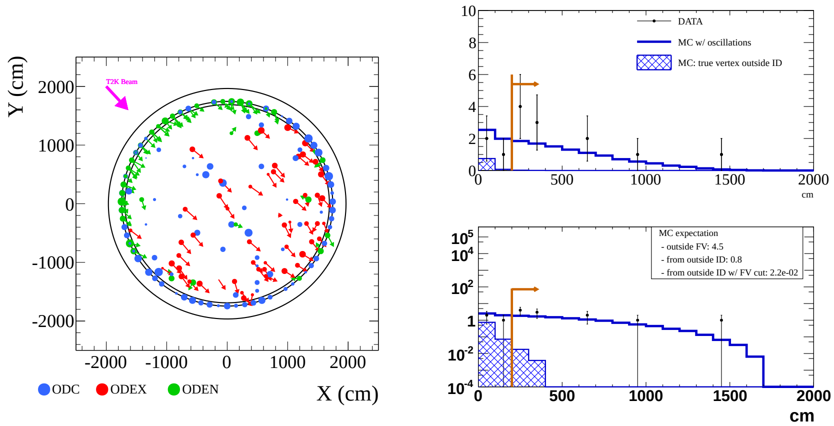


Figure 12: Left: X-Y coordinates of reconstructed interaction vertices for beam events which pass all the OD reduction cuts for T2K Run 1+2+3. Right: contamination in the ν_e sample from outside the OD.

Multi-Ring Studies (Himmel, Walter): During the first ν_e oscillation analyses there were some distributions of multi-ring events which had unusual properties. Walter led a "Multi-Ring Task Force" to determine whether this was anything more than a statistical fluctuation by examining known systematic effects. No evidence for non-statistical fluctuations were found. Himmel continued this work by carefully documenting the output of the task force in a technical note, extending the work and now looking at the new beam data to see if any of the discrepancies still exist. The new data are consistent with the previous effect being a fluctuation.

Systematic Studies: (Albert, Walter): Albert studied the systematics of the T2K NC π^0 rejection algorithm by constructing fake π^0s out of single-ring electron-like atmospheric neutrino events and decay electrons. This sample simulated the asymmetric decay of π^0s and can be used to compare the response of our algorithms between data and MC to very low energy rings in the events. Rejection of π^0s is one of the most critical steps in background reduction for the experiment.

Preparation of Current T2K Oscillation Results (Scholberg, Walter, Wendell, Wongjirad): Walter chaired the review committee which oversaw and reviewed the three internal ν_e oscillation analyses, and Scholberg is currently chairing the ν_μ analysis review committee, in addition to participation on committees which oversaw the production of T2K systematic errors from SK. Wongjirad produced new T2K OD MC and did the OD reduction along with the entering background estimates. Wendell performed stability and performance checks with the SK IV atmospheric data.

8.2.3 LBNE Contributions

For LBNE, our primary physics interests relate to neutrino oscillation, proton decay and supernova neutrinos. Walter received an NSF CAREER award for work on this project. We have also received NSF support for this project (via the "S4" solicitation), 2010-2012. Scholberg was elected to the Executive Committee of LBNE in January 2010 for a two-year term, and reelected for another two years in 2012. In 2011 she served as co-editor of the "1+1" document given to the Marx committee, for which Walter also presented the simulation status and PMT coverage rationale. Scholberg served on the PMT Selection Committee and the Light Collector Review Committee and served in the Reconfiguration Physics Working Group. Until the LBNE technology decision, we primarily worked in the Water Cherenkov (WC) part of the collaboration, because of our extensive experience with this technology. Since the technology decision at the beginning of 2012, we have become involved with liquid argon.

Water Cherenkov Simulations (Walter, Scholberg, Chan, Beroz, Prendki, Akiri, Himmel, Li): Walter led the LBNE WC simulation group. He has continued to guide the development of the simulation program. In the last few years he led the work towards full MC-based physics reconstruction studies for the LBNE WC detector. This meant both careful tuning of the optical models and also the formidable task of modifying the SK reconstruction code to work in the 200 kton design. He coordinated all of the work in our collaborating institutions including Boston, Irvine, FNAL and Caltech. Under Walter's leadership, the simulation group had real impact on the design process for LBNE. In the last two years, the simulations working group worked on reconstruction studies using 12% coverage high-quantum efficiency PMTs, studied light collection efficiencies, and implemented complete photon tracking and light collector options in the simulation. At Duke, simulations of various detector options and use of the SK reconstruction tools allowed us to validate our reference design and present it to the Marx committee at SLAC in April of 2011. Akiri and Himmel worked with Lozier to more carefully match the SK geometry in the simulation and then undertook a tuning campaign which involved simulating a laser calibration system and particle data. This work achieved 3% level agreement and we are now exploring how to use WCSim inside of SK and T2K. Improvements to the core GEANT4 optical propagation code were also passed back to the GEANT4 maintainers where they benefited the entire community. WCSim continues as a community resource and several groups are using it for their own work.

Supernova Burst Physics (Scholberg, Beck, Beroz, Borhanian, Johnson, Kaiser): Scholberg is convener of the LBNE Supernova Burst Physics Working Group. This is one of the working groups charged with evaluating physics reach of different WC and LAr detector configurations; it is now focusing on LAr sensitivity. The preliminary report of the working group was published in October [19]. The working group has developed general-purpose code, called SNOwGLoBES (`http://www.phy.duke.edu/~schol/snowglobes`), to produce event rate spectra for given fluxes and parameterized detector responses. This code has been made publicly available.

LBNE Project Contributions (Fowler, Scholberg): For the WC group of LBNE, engineer Fowler worked with the water containment and water system groups. Since the LAr detector decision, Fowler has been working with several different groups. He was appointed as the project engineer for the 35-ton test cryostat at FNAL. In this position he is responsible for the development, scheduling, planning and testing of components and prototypes from all of the LAr subsystems in the 35-ton tank.

Liquid Argon Simulations (Scholberg, Li): In 2012 Scholberg started work with the LArSoft group, with the main interest of exploring sensitivity of liquid argon TPCs to low energy events such as would be produced by supernova neutrinos. The detector response to this kind of event has been poorly studied and reconstruction algorithms are essentially nonexistent. Graduate student Li has started work on this topic, and has been contributing to photon simulations. Scholberg has also begun studying cosmogenic backgrounds in liquid argon (in particular for low energy events), for which it will be vital to understand the impact for a surface detector.

8.2.4 Additional Activities

Scholberg is the coordinator of SNEWS, the SuperNova Early Warning System and makes a modest contribution to HALO (the Helium and Lead Observatory). These activities are supported by NSF and involve mainly undergrads. Scholberg also participates in DAEδALUS discussions. The activities occupy less than 10% of Scholberg's research time.

8.2.5 Service to the Physics Community

Scholberg served on HEPAP from 2008-2010. She served on the Canadian NSERC Grant Selection Committee (2007-2010) and the Canadian Long Range Planning Committee for Subatomic Physics in 2011. She was elected to the DPF Executive Committee for a three-year term in 2009. She was elected to the Deep Underground Research Association Executive Committee for a three-year term in 2011. Walter and Scholberg have served on several NSF and DOE review panels which included, in addition to grant review panels, the NSF Frontier Center panel (Walter), DOE FNAL S&T panel (Walter) and DOE Committee of Visitors (Scholberg). Both Scholberg and Walter have served on organizing committees, scientific advisory boards or as session conveners for several conferences. Walter was one of the initial organizers of the NuInt conference series, continuing in this role since 2001. Scholberg was a co-convener of the Intensity Frontier Workshop neutrino group in 2011 and was a primary author of the neutrino section of the resulting document [12]. She is co-convener of Neutrino and of Non-Accelerator Capabilities working groups for Snowmass 2013 activities.

8.3 Publications

We include here publications since 2010 for which group members have made intellectual contributions. For multi-author publications, the nature of the contribution is indicated.

[1] Super-K Collaboration, SK IV solar paper, in preparation. *AH on author committee*

[2] T2K Collaboration, NC gamma cross-section paper, in preparation. *AH on author committee*

[3] T2K Collaboration, ν_μ disappearance paper, in preparation. *KS on author committee*

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[5] V. Cianciolo, A. B. Balantekin, A. Bernstein, V. Cirigliano, M. D. Cooper, D. J. Dean, S. R. Elliott and B. W. Filippone *et al.*, "Discovering the New Standard Model: Fundamental Symmetries and Neutrinos," arXiv:1212.5190 [nucl-ex].

[6] K. M. Patton, G. C. McLaughlin and K. Scholberg, "Prospects for Using Coherent Elastic Neutrino-Nucleus Scattering to Measure the Nuclear Neutron Form Factor", International Journal of Modern Physics E. 22 (2013) 1330013.

[7] K. Abe *et al.* [T2K Collaboration], ‘Evidence of Electron Neutrino Appearance in a Muon Neutrino Beam,” arXiv:1304.0841 [hep-ex]. *CW on author committee.*

[8] Super-K Collaboration, “Calibration of the Super-Kamiokande Detector,” arXiv:1307.0162 [physics.ins-det]. *KS author of OD section*

[9] K. Abe *et al.* [Super-Kamiokande Collaboration], “Evidence for the Appearance of Atmospheric Tau Neutrinos in Super-Kamiokande,” Phys. Rev. Lett. 110, **181802** (2013) [arXiv:1206.0328 [hep-ex]]. *CW primary author*

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[13] A. J. Anderson, J. M. Conrad, E. Figueroa-Feliciano, C. Ignarra, G. Karagiorgi, K. Scholberg, M. H. Shaevitz and J. Spitz, Phys. Rev. D **86**, 013004 (2012) [arXiv:1201.3805 [hep-ph]]. *KS contributing author.*

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[16] K. Abe *et al.* [T2K Collaboration], “Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam,” Phys. Rev. Lett. **107**, 041801 (2011) [arXiv:1106.2822 [hep-ex]]. *JA primary author; CW, TW, KS contributors.*

[17] K. Abe *et al.* [T2K Collaboration], “The T2K Experiment,” Nucl. Instrum. Meth. A **659**, 106 (2011) [arXiv:1106.1238 [physics.ins-det]]. *TW author of SK section.*

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[22] K. Nakamura *et al.* [Particle Data Group Collaboration], “Review of particle physics,” J. Phys. G **G37**, 075021 (2010). *KS, CW authors of “Deep, liquid underground detectors” review.*

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[25] R. Wendell *et al.* [Super-Kamiokande Collaboration], “Atmospheric neutrino oscillation analysis with sub-leading effects in Super-Kamiokande I, II, and III,” Phys. Rev. **D81**, 092004 (2010). [arXiv:1002.3471 [hep-ex]]. *RW primary author; KS on author committee.*

Presentations are listed at **http://www.phy.duke.edu/∼schol/talklist-report.pdf**.