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Senior Investigators

Experimental Physicists: Todd Adams, Andrew Askew, Susan Blessing, Harrison B. Prosper, Horst D. Wahl

Theoretical Physicists: Bernd Berg, Takemichi Okui, Joseph F. Owens, Laura Reina

1 Introduction

This document highlights the main research accomplishments of the Florida State University High Energy Physics (FSUHEP) Group, focusing on the three-year period ending 4/30/2013. During this period, the experimental group completed work on the DØ Experiment at Fermilab and completed its transition to the CMS Experiment at CERN. The theoretical physics group worked on quantum chromodynamics (QCD), Higgs boson physics, beyond the standard model (BSM) physics, and lattice field theory (LFT). The membership of the FSUHEP group underwent significant changes since 2008, due to retirements, resignations, and appointments. At the end of the grant period, the group comprised three experimental physicists (Adams, Askew, and Prosper) and four theoretical physicists (Berg, Okui, Owens, and Reina). However, for completeness, we list below all investigators who were associated with the group at some point during the recent grant period. There were two notable additions to the group, Dr. Takemichi Okui, a theorist, and Dr. Andrew Askew, an experimentalist, who joined the Florida State University Physics Department in fall 2009 as Assistant Professors.

In order to highlight the contribution of each funded member of the group, the work of the Principal Investigator and each of the Co-Principal Investigators is described individually. However, in reading this report, it is useful to bear in mind an important aspect of the FSUHEP group, namely, the synergy between its experimental and theoretical work. A typical example is the collaboration between former graduate students Dan Duggan (Ph.D., 2009) and Tzvetalina Stavreva (Ph.D., 2009). Duggan measured the photon plus heavy quark cross section at the Tevatron, under Horst Wahl's supervision, while the theoretical prediction for the cross section was performed by Stavreva under the direction of Jeff Owens. Another example of synergy is the collaboration between experimentalist Todd Adams and theoretical physicist Takemichi Okui. Okui constructed several models of potential new physics that inspired searches at the Large Hadron Collider (LHC) by Adams and co-workers. A third example is the work at the Tevatron on the W boson production charge asymmetry by Susan Blessing and Andrew Askew and its beneficial impact on Owens' work on parton distribution functions (PDF). Not only does this synergy yield interesting scientific results, it also makes for an intellectually cohesive and vibrant group.

Investigators

Experimental Physicists

Todd Adams – Professor (Ph.D. 1997, U. Notre Dame); CMS, exotica/SUSY searches, CMS Electromagnetic Calorimeter (ECAL), calorimeter upgrade.

Andrew Askew – Assistant Professor (Ph.D. 2004, Rice U.); CMS, new physics with photons, ECAL.

Susan K. Blessing – Professor (Ph.D. 1989, Indiana U.); DØ, electroweak physics.

Harrison B. Prosper – Professor (Ph.D. 1980, Manchester U.); CMS, Higgs boson physics, SUSY searches, advanced analysis methods.

Horst D. Wahl – Professor (Ph.D. 1969, U. Vienna); DØ, QCD.

Theoretical Physicists

Bernd Berg – Professor (Ph.D. 1977, Freie Universität of Berlin); Lattice field theory.

Takemichi Okui – Assistant Professor (Ph.D. 2003, U. California, Berkeley); Model building and phenomenology beyond the standard model, cosmology, effective field theories.

Joseph F. Owens – Professor (Ph.D. 1973, Tufts U.); QCD calculations for hard-scattering processes, determination of parton distributions.

Laura Reina – Professor (Ph.D. 1992, International School for Advanced Studies, Trieste, Italy); QCD, Higgs boson physics, collider phenomenology.

Other Investigators

Below we list all postdocs who were associated with the group during the grant period. The number of postdocs in the group at any given time ranged from two to four.

Postdoctoral Associates

Dmitry Bandurin – Assistant in Research (Ph.D. 2004, Moscow State U.); DØ, QCD and new phenomena with photons, QCD Convener, Jet Energy Scale Convener.

Jie Chen – Assistant in Research (Ph.D. 2008, U. Kansas); CMS, event simulation, searches for heavy stable charged particles, ECAL.

Prerit Jaiswal – Assistant in Research (Ph.D. 2012, Stony Brook U.); Higgs phenomenology, EW baryogenesis in new physics models, collider signatures of new physics in the electroweak sector, dark matter.

Alejandro Jenkins – Research Associate (Ph.D. 2006, CalTech); New applications of effective quantum field theory methods.

Seth Quakenbush – Assistant in Research (Ph.D. 2009, U. Wisconsin, Madison); Tools for next-to-leading order calculations, hadron collider phenomenology precision EW measurements.

Loic Quertenmont – Research Associate (Ph.D. Université Catholique de Louvains, 2010); CMS, heavy stable charged particles, $\mathrm{d}E/\mathrm{d}x$, visualization software.

Thomas Schutzmeier – Research Associate (Ph.D. 2009, U. Würzburg, Germany); Automation of higher order quantum field theory calculations, NLO corrections to $W+b$+jet at hadron colliders, vector boson production with $t\bar{t}$ pairs.

Sezen Sekmen – Research Associate (Ph.D. 2008, Middle East Technical U.); CMS, SUSY searches and SUSY phenomenology.

Marc G. Weinberg – Assistant in Research (Ph.D. 2011, U. Wisconsin, Madison); CMS, new physics with photons, electroweak physics.

Senior Investigators

Kurtis Johnson – Computer Research Specialist (Ph.D. 1987, U. Chicago); CMS, FSU Tier 3 Center, Higgs boson physics.

Sharon Hagopian – Emeritus Staff Physicist (Ph.D. 1970, U. Pennsylvania); CMS, Hadronic Calorimeter (HCAL).

Vasken Hagopian – Emeritus Professor (Ph.D. 1963, U. Pennsylvania); CMS, HCAL.

Ph.D. Students Supported (2010–2012)

Listed below are the names of the graduate students who were supported in part by DOE funds, along with the year each student entered graduate school and her, or his, major professor and activities.

Andrew Ackert – 2012, T. Adams, CMS.

Jordan Adams – 2010, A. Askew, CMS.

Samuel Bein – 2011, H.B. Prosper, CMS.

Joseph Bochenek – 2008, H.B. Prosper, CMS.

Brendan Diamond – 2007, T. Adams, CMS.

Christopher Duston – 2007, M. Marcolli (Mathematics) and L. Reina.

Jeffrey Haas – 2006, H.B. Prosper, CMS.

Heribertus Hartanto – 2007, L. Reina, theory.

Ajeeta Khatiwada – 2010, S. Blessing and A. Askew, CMS.

Karoline Köpp – 2009, T. Okui, theory.

Ben Thayer – 2005, L. Reina, theory.

Venkatesh Veeraraghavan – 2007, T. Adams, CMS.

Arka Santra – 2011, A. Askew, CMS.

Nobuo Sato – 2008, J.F. Owens, theory.

David Westmark – 2008, J.F. Owens, theory.

Christopher Zeoli – 2011, T. Okui, theory.

Hao Wu – 2007, B. Berg, theory.

Ph.D.s Awarded (2010–2012)

Sergei Gleyzer – "The Search for Dark Matter in the Lepton-jet Final State at $\sqrt{s} = 7$ TeV," with V. Hagopian, 2011.

Trang Hoang – "Measurement of the Muon Charge Asymmetry in $p\bar{p} \to W + X \to \mu\nu + X$ Events Using the D0 Detector," with S. Blessing, 2012.

Paulo Rottman – "Z-Sum Approach to Loop Integrals," with L. Reina, 2011.

Benjamin Thayer – "On-Shell Method Applied to Exotic Higgs Production at Hadronic Colliders," with L. Reina, 2012.

Hao Wu – "Deconfinement transition in equilibrium lattice gauge theory with realistic boundary conditions," with B. Berg, 2012.

The following Ph.D.s, which were the culmination of work performed during the grant period, were awarded within months of the end of the grant period: **Jeffrey Haas** – "Search for contact interactions using the inclusive jet p_T spectrum in pp collisions at $\sqrt{s} = 7$ TeV," with H.B. Prosper, May 2013; **Joseph Bochenek** – "The Higgs Boson: The Search for the Standard Model Higgs Boson and Investigation of its Properties," with H.B. Prosper, August 2013; **Heribertus Hartanto** – "Heavy-quark Associated Production with One Hard photon at Hadron Colliders," with L. Reina, August 2013; **Karoline Köpp** – "Topics in Physics Beyond the Standard Model," with T. Okui, May 2013, and **Venkatesh Veeraraghavan** – "Search for Multiply Charged Heavy Stable Charged Particles in Data Collected with the CMS Detector," with T. Adams, December 2013.

2 Experimental Physics Program

Senior Personnel: T. Adams, A. Askew, S. Blessing, H.B. Prosper, and H.D. Wahl

Postdoctoral Associates: D. Bandurin and M. Weinberg

Graduate Students: A. Ackert, J. Adams, S. Bein, J. Bochenek, B. Diamond, S. Gleyzer, J. Haas, T. Hoang, A. Khatiwada, A. Santra, and V. Veeraragahavan

This section covers the accomplishments of Senior Researchers Adams, Askew, Blessing, Prosper, and Wahl, for the period 1/1/2010 – 4/30/2013. This was a period of transition from work on both the DØ and CMS Experiments to work on the CMS Experiment exclusively. We do not give a comprehensive survey of all the work done. Instead we highlight the most important contributions that illustrate the breadth of the research activities.

2.1 T. Adams (CMS)

Searches for Heavy Stable Charged Particles Heavy stable charged particles (HSCP) are a characteristic prediction of many theories of physics beyond the standard model (see for example Ref. [1] and references therein). Therefore, the discovery of such particles would provide spectacular evidence of new physics. The basic approach is to search for particles with large dE/dx and/or long time-of-flight to separate HSCP candidates from standard model particles. T. Adams is a leader in the search for HSCPs at CMS, while former postdoc Chen and graduate student Veeraraghavan were two of the primary analysts. Veeraraghavan's dissertation was based on the 2011–2012 CMS data. T. Adams is one of two senior faculty members who lead the CMS HSCP group and therefore responsible for the papers and public analysis notes produced by the group.

Two papers on LHC data [2, 3] have been published. Most of the HSCP analysis results [3]) focused on singly-charged particles in which either the tracker was used (to measure dE/dx) or in which both the tracker (dE/dx) and the muon system was used (to measure time-of-flight). The second technique allows for a better background reduction while the former addresses the possibility that the HSCP could become neutral prior to reaching the muon system. No signal was observed, but T. Adams and co-workers were able to set some of the world's best limits on these models: mass limits of >1091 GeV/c^2 (gluinos), >735 GeV/c^2 (stops), and >232 GeV/c^2 (staus) at 95% CL [3].

FSU theorist Okui developed a new model several years ago called vector-like confinement that predicts the possibility of new HSCP candidates [1]. An interesting aspect

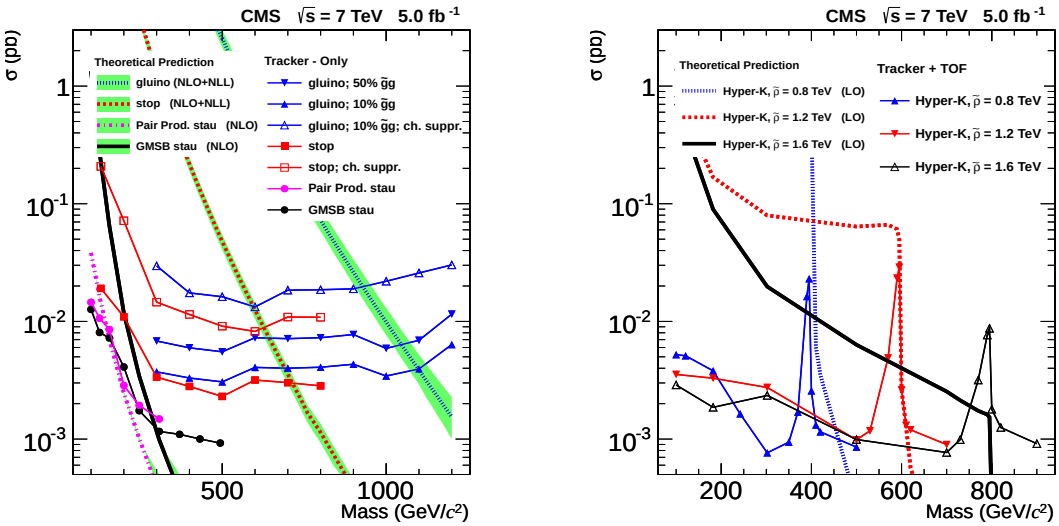

Figure 1: Predicted theoretical cross section and observed 95% C.L. upper limits on the cross section for the different HSCP models using 5 fb^{-1} of 2011 data [3]. The left plot is for the tracker-only analysis for various SUSY models, while the right shows the tracker+TOF results applied to resonant and non-resonant di-CHAMPs from the Okui vector-like confinement model.

of this model is that it predicts resonant production of a pair of HSCPs (also referred to as di-CHAMPs in the literature). Chen and T. Adams worked with Okui *et al.* to understand the model and incorporate it within the CMS search. The 2011 publication [3] includes the first direct experimental limits on this vector-like confinement model (see Fig. 1).

T. Adams and Chen continuously pushed to expand and improve the HSCP analysis. They first proposed exploring higher and lower charged particles (see below). T. Adams proposed a two dimensional likelihood technique that uses more information, can simplify the analysis, achieve better background to signal separation, and is more sensitive to HSCP signals.

T. Adams, Chen, and Veeraraghavan conducted a new search for highly charged ($Q > |1e|$) particles in the CMS 2011 data. Such particles are predicted by models including Q-balls [4], stable micro black-hole remnants [5], magnetic monopoles [6], and dyons [7]. These particles would represent striking evidence of physics beyond the standard model in the form of a very highly ionizing track in the detector. Cross section and mass limits on particles with charges 1–5e have been obtained (Fig. 2(left)) and was the dissertation topic of Veeraraghavan. His results were presented at ICHEP12 [8].

In addition, Chen worked with colleagues from Ohio State on a search for fractionally charged particle (which he proposed). Results were shown at ICHEP12 [9]. Figure 2(right) summarizes mass limits on various HSCP models as a function of charge.

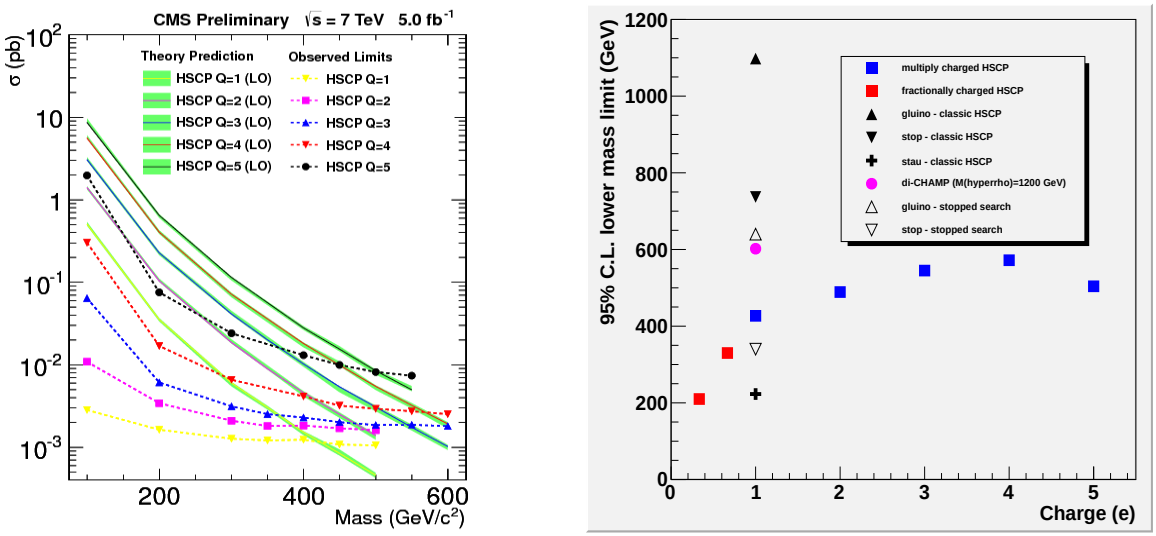

Figure 2: (left) Predicted theoretical cross section and observed 95% C.L. upper limits on the cross section for the different charges of pair-produced HSCPs using 5 fb^{-1} of 2011 data [8]. (right) 95% C.L. upper limits on various HSCP models as a function of mass.

Previously only $Q = 1$ had been investigated, but thanks to FSU's leadership a range of charges have now been considered. FSU members are primary authors on all of the results in Fig. 2(right) except for the stopped HSCP searches (open triangles).

T. Adams, Ackert, and former student Veeraraghavan search for evidence of new heavy, (quasi-)stable, charged particles (HSCPs) in the CMS data. The latest result was published in 2013 as a compilation of five separate analyses [10]: tracker-only, tracker+time-of-flight, muon-only, multiply charged, and fractionally-charged. Veeraraghavan and T. Adams were the primary authors of the multiply charged analysis searching for long-lived particles with charge $> |1e|$. T. Adams wrote the draft of the complete paper and guided it through the review process.

CMS Resonance Search with Three Photon Events Diamond and T. Adams worked on a search for a narrow resonance in the two photon mass spectrum of three photon events. This search was inspired by the work of Okui *et al.* [1, 11]. In the Okui model, a new symmetry is added to the standard model that results in a spectrum of bound states of "hyperparticles". Depending on model parameters, resonant production of a charged hyper-rho meson can lead to decay to a charged hyper-pion and a neutral hyper-pion. In the model of interest, the neutral hyper-pion decays to two photons while the charged hyper-pion decays to a photon and a W boson. This leads to a three photon final state with two of the photons originating from a narrow resonance.

Diamond performed a search for this narrow resonance in the di-photon mass spec-

trum of three photon events. No evidence of such a resonance is found in the 200-600 GeV/c^2 mass range.

CMS Calorimeter Upgrade Studies Initial estimates indicate that by 2022, the CMS forward electromagnetic crystal calorimeter will turn opaque because of radiation damage. T. Adams and Askew led (and continue to lead) FSU's contributions to the planning for a forward calorimeter suitable for the LHC High Luminosity (LHC-HL, 2024-2033) program. Our students and postdocs have contributed to testbeam experiments that are being used to understand the expected performance of the current CMS calorimeter.

T. Adams, Ackert, and several undergraduate students have studied the proposed Shashlik calorimeter upgrade to the CMS endcap calorimeter. The CMS collaboration is considering two technologies to replace partially or completely the forward calorimeter. The Shashlik calorimeter uses tungsten and LYSO plates with fibers running through them. The High Granularity Calorimeter (HGC) uses silicon pads between tungsten plates. A decision on which technology to pursue is anticipated in 2015.

Much of the work by T. Adams and his students is based on a standalone Shashlik calorimeter upgrade simulation, which this group developed. The work was led by T. Adams. The simulation is a simplified version of the endcap calorimeter. It is called "standalone" because it works outside of the CMS software system (CMSSW) and has the advantage of being fast and easy to reconfigure.

2.2 A. Askew (CMS)

ECAL and e/γ Efforts Askew was one of the first to observe anomalous signals from neutron interactions in the CMS photodetectors in early 2010, and anomaly that quickly became a source of concern. Askew and his student J. Adams studied how these signals, referred to as "spikes", modify the energies observed in real electromagnetic showers from electrons and photons. These studies were the basis of an algorithm to flag these anomalies and correct the cluster energies in the CMS electromagnetic calorimeter (ECAL).

Askew, along with postdoc Weinberg, and students J. Adams, Khatiwada and Santra, worked on tasks in support of electromagnetic calorimeter performance monitoring and enhancement, as well as e/γ reconstruction and identification. Khatiwada investigated how to mitigate the effect of spurious events, the so-called spikes, in the CMS Level 1 (L1) trigger. With the anticipated instantaneous luminosity at 13 TeV (the collision energy of Run II of the LHC, scheduled to start in 2015), the present thresholds in the L1 trigger would result in an unsustainable trigger rate. It was determined that with a retuned trigger threshold, the trigger rate can be controlled with minimal loss in efficiency for electromagnetic showers.

Askew, Santra and Weinberg made significant contributions to the ECAL clustering and energy corrections. The software for building energy clusters and then electron and photon physics objects has been significantly revised in order to facilitate integration with the CMS Global Event Description (GED). The GED uses the particle flow reconstruction method, which attempts to reconstruct the energy and momentum of every particle in an event. Weinberg has written tools for deriving the cluster energy corrections as a function of energy and rapidity. He also studied the performance of the clustering algorithms. Santra has worked with the cluster energy corrections, which will be improved to make use of a multivariate regression to correct the visible energy.

J. Adams and Askew investigated the expected response and resolution of the ECAL (barrel and endcap) for higher doses of radiation and additional pileup interactions (multiple overlapping events arising from multiple proton-proton interactions during proton bunch crossings). The increase in radiation damage leads to both substantial light loss (through loss of transparency in the crystals, which is most relevant in the endcap) and increased dark currents in the photodetectors, which can substantially alter the performance in the barrel calorimeter. J. Adams and Askew collaborated with colleagues from Notre Dame on the tuning of relevant clustering parameters for these future scenarios in an attempt to preserve as much as possible the present ECAL detector performance.

Exotic Searches with Photons The CMS electromagnetic calorimeter was designed to have a very high resolution and efficiency for photons for use in the successful search for $H \to \gamma\gamma$. The high resolution also allows for highly sensitive searches for new physics using photons.

There are many models of new physics that predict reactions in which a photon is produced in association with a particle that escapes detection, such as models of large extra dimensions [12] and dark matter production [13]. The dark matter searches, in particular, provide additional sensitivity that is complementary to that of dedicated direct searches. There also exist scenarios for new physics with vectorlike confinement that can give rise to final states with as many as three high transverse energy photons [1], which are distinctive collider signatures.

Askew has been leading a search for large extra dimensions and dark matter in the photon plus missing transverse energy channel. This analysis is complicated by a plethora of backgrounds: hadron showers, electrons, beam halo, cosmics, and even anomalous signals from the ECAL itself. Meanwhile, the signal is non-resonant, and the only observable object in the event is the photon itself. Askew has been leading the overall analysis strategy, and in particular the estimation of the out of time backgrounds by making use of the ECAL timing (aided by Weinberg).

The completed 2011 analysis culminated in a publication [14], in which the collider sensitivity to dark matter signatures was made manifest (see Fig. 3). Together with

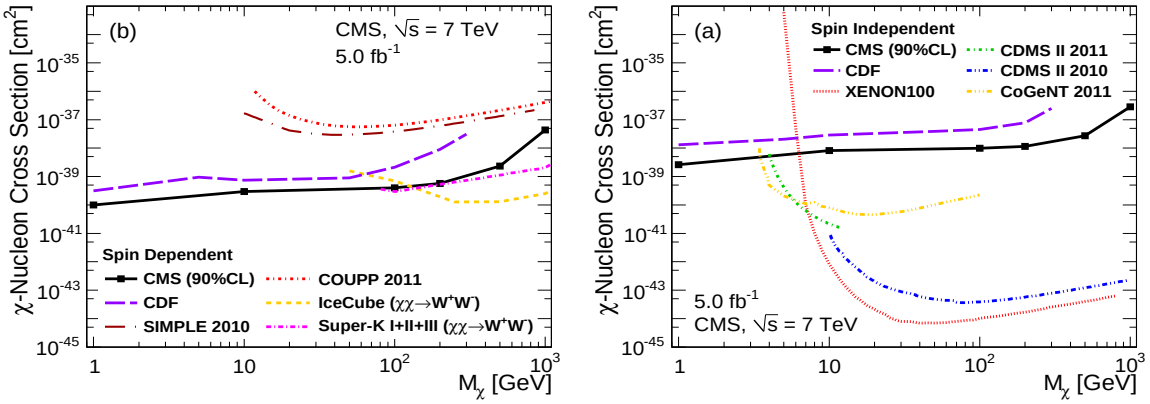

Figure 3: 90% C.L. limits on the dark matter-Nucleon cross section as a function of dark matter mass from CMS monophoton search. Also shown: selected limits from other direct/indirect searches.

similar monojet topology searches, additional new constraints have been added to dark matter production and large extra dimensions. Additionally, the monophoton analysis may be reinterpreted as a study of the anomalous coupling of the Z boson to the photon (where the Z boson decays to neutrinos). The sensitivity to anomalous couplings is largely at high photon transverse energy, therefore, even though the single photon threshold is much higher than in the charged lepton analyses, the monophoton channel is typically a factor of three more sensitive (given the three generations of neutrinos). This additional study is presently underway.

SUSY Searches With Photons Models of SUSY with Gauge Mediated Breaking (GMSB) give rise to final states with vector bosons and missing transverse energy. These vector bosons are often produced at the end of a cascade decay of SUSY particles, and the missing transverse energy originates from the escape of the lightest supersymmetric particle, in this case, the gravitino. For a substantial portion of the parameter space, these models predict final states with one or more photons. Recently, models of SUSY augmented by a hidden sector, so-called "Stealth SUSY" [15], can yield signatures similar to the above, but with low missing transverse energy.

Weinberg (with collaborators from Fermilab and Rutgers) developed a method by which the S_T distribution (the sum of the E_T of jets, photons and missing E_T) for the relevant (high) jet multiplicity bins could be derived from the data using low multiplicity bins. The results from the 2011 data are shown in Fig. 4. This result was made public for the 2012 summer conferences. The method itself is quite powerful in cases where S_T scaling holds, and can provide sensitivity in multiple different event topologies to various models of new physics. The current search represents only the beginning of a family of searches of this type.

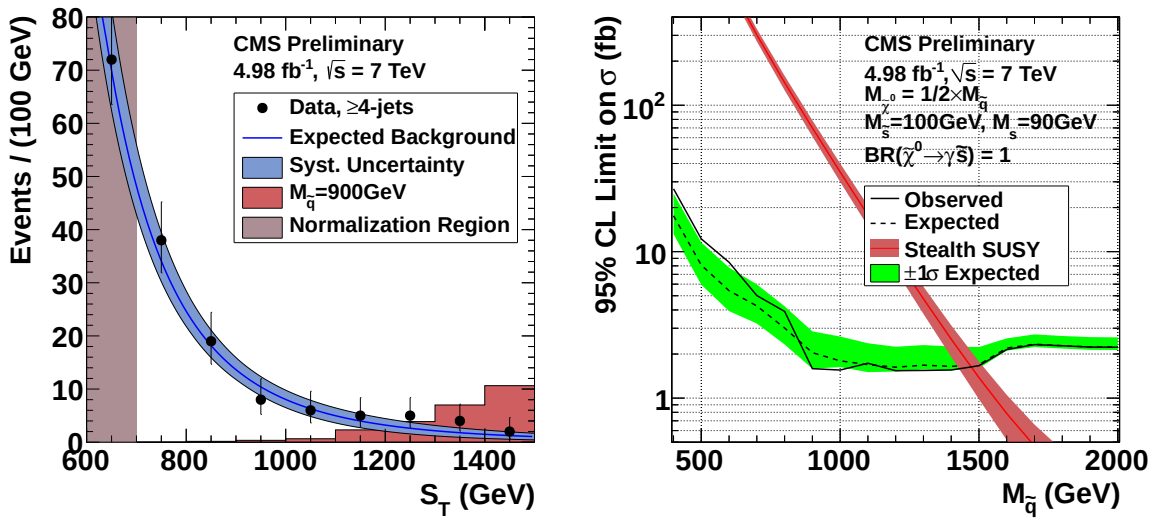

Figure 4: Performance of present "Stealth SUSY" search. The left plot demonstrates the data based background prediction in the S_T variable, the candidate data, and the expected signal from a 900 GeV squark. The right plot shows the cross section limit as a function of squark mass from the 2011 dataset.

Standard Model Physics The successful 2011 monophoton analysis, in which Askew played a lead role [14] has been reinterpreted in terms of a $Z\gamma \to \nu\nu\gamma$ cross section measurement which was subsequently published [16]. The best limits yet on anomalous coupling of the Z to the photon were set using the photon transverse energy distribution, and combined with the charged lepton channels.

Khatiwada is working with Askew on the triple differential direct photon cross section analysis in the 8 TeV data, which should be her dissertation research.

Exotica Askew continues to play a leading role in the monophoton analysis using the 8 TeV data. The challenge of this new dataset over the published 7 TeV analysis is mainly due to the increase in the number of interactions per crossing, which leads to pileup. Several important aspects of the previous analysis, such as the jet and track vetoes in the selection, showed such a large dependence on the number of interactions that the analysis needed an overhaul so that sensitivity could be maintained in the 8 TeV data.

Supersymmetry Askew, Weinberg, J. Adams and Santra have pursued analyses, within the CMS SUSY Group, using the 8 TeV data. Askew and Santra worked on searches for gauge mediated supersymmetry breaking in diphoton plus missing

transverse energy events while Weinberg and J. Adams pursued searches for supersymmetry with low missing transverse energy.

Askew and Santra conducted a search for new physics in diphoton events with large missing transverse energy. These final states are sensitive to a range of new physics scenarios, though most commonly found in gauge mediated supersymmetry breaking (GMSB) models. Central to this analysis is the estimation of the background from events with missing transverse energy which results from mismeasurement of hadronic activity. The large statistics and challenging environment have lead to substantial differences between the data control samples that were previously used to each model the distribution of the missing transverse energy, believed to originate from a difference in the response to hadronic jets mimicking photons and real electromagnetic showers from photons/electrons In collaboration with colleagues from Fermilab and Notre Dame, a new technique for making a data based estimate of the shape of the missing transverse energy distribution from these backgrounds has been proposed, a departure from the technique used in previous searches [17, 18].

2.3 S. Blessing (DØ)

W boson production charge asymmetry Blessing has made several measurements of the W boson charge asymmetry, using both the $W \to e\nu$ and $W \to \mu\nu$ channels. The first measurement, by Blessing and S. Sengupta (FSU Ph.D. 2006), used 0.3 fb^{-1} of Run IIa data in the $W \to \mu\nu$ channel and was published in early 2008 [19]. Askew worked on the $W \to e\nu$ asymmetry analysis, using 0.75 fb^{-1} of Run IIa data to make what was, at the time, the world's most precise measurement of the lepton charge asymmetry from W boson decay [20].

The W boson production charge asymmetry is directly sensitive to the ratio of the momentum carried by the up quark to that of the down quark. At a hadron collider, almost every analysis makes use of parton distribution functions (PDFs), determined from fits of phenomenological models of parton densities to a large variety of experimental data. This is one of the critical theoretical contributions of the CTEQ collaboration (among others) of which Owens is a founding member.

Since up quarks carry more of the momentum of a proton than do down quarks, W^+ bosons tend to move in the direction of the proton and W^- bosons in the direction of the anti-proton. It is difficult to determine the rapidity of the W boson directly because the longitudinal momentum of the neutrino is not measured. However, the rapidity of the charged lepton from $W \to l\nu$ decay is readily measured. The $V - A$ nature of the weak interaction introduces an additional factor in the angular distribution of the charged lepton, but this contribution can be calculated. Although the analysis is basically a counting experiment, it is challenging because it requires a complete understanding of efficiencies, backgrounds, and the charge misidentification probability as well as a careful assessment of uncertainties.

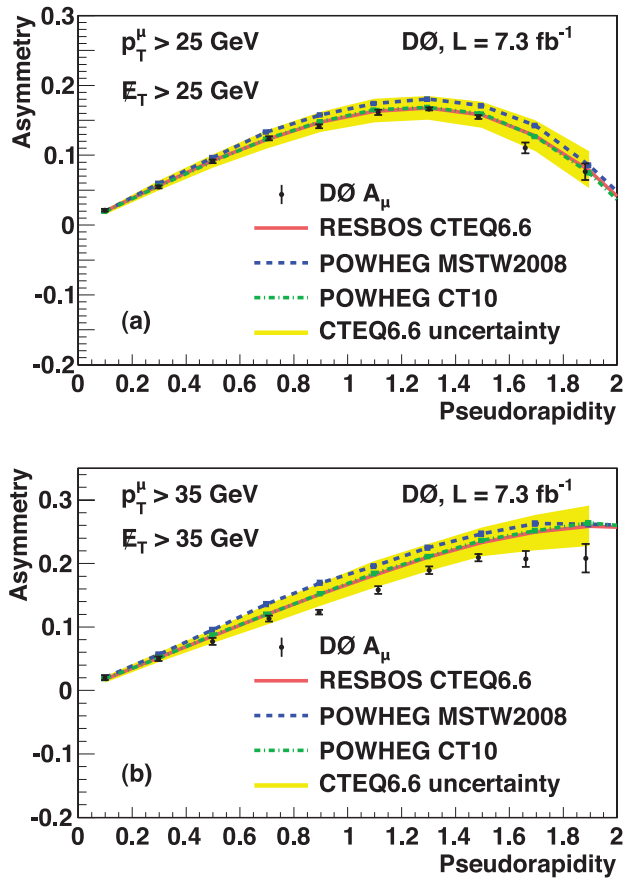

Figure 5: The muon charge asymmetry vs. muon pseudorapidity for (a) ($p_T^\mu > 25$ GeV and $\not{E}_T > 25$ GeV) and (b) ($p_T^\mu > 35$ GeV and $\not{E}_T > 35$ GeV). The black points show the muon charge asymmetry measured with 7.3 fb^{-1} of integrated luminosity. The error bars represent the total uncertainties. The solid line and the band are the central value and uncertainty band of the RESBOS+PHOTOS with CTEQ6.6 prediction. The predictions from POWHEG with the MSTW2008 and CT10 PDF sets are also shown.

Hoang and Blessing studied $W \to \mu\nu$ with 7.3 fb^{-1} of Run II data. This large dataset significantly reduces the statistical uncertainties of the measurement and yields greatly improved background estimates. It also allows us to measure the asymmetry in two p_T^μ bins. The Run IIa dataset plays an important role. Owing to its lower instantaneous luminosity, events from single muon triggers are available that cover the forward rapidity region from 1.6 to 2.0. The higher instantaneous luminosity of Run IIb forced a reduction in the rapidity coverage of the single muon trigger.

Hoang defended her Ph.D. dissertation in November 2012. Blessing did the work needed to finalize the analysis for publication, and it was published in Physical Review Rapid Communications in November 2013 [21].

Figure 5 shows the results of this work. At lower lepton p_T, the lepton charge asym-

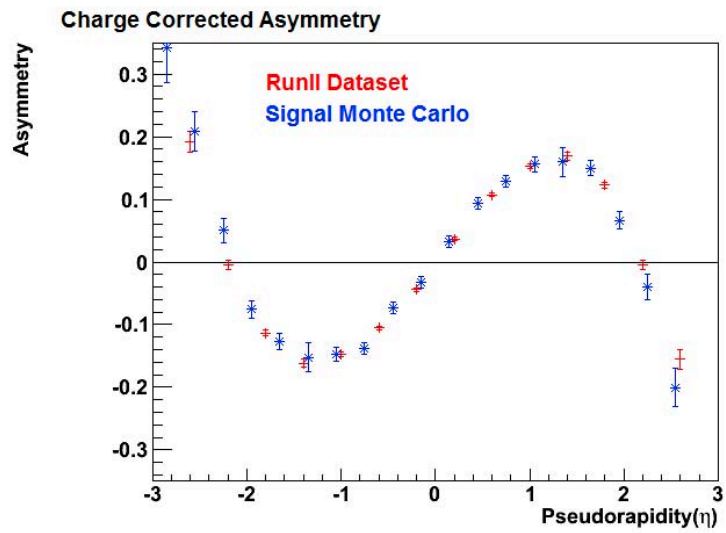

Figure 6: Electron charge asymmetry from W boson decay without full background subtraction.

metry is strongly influenced by the V–A decay of the W boson. At large lepton p_T, the lepton charge asymmetry is closer to the W boson production asymmetry, leading to the different shapes of Figs. 5(a) and 5(b). The data at $p_T^\mu > 35$ GeV, $\not{E}_T > 35$ GeV, and larger values of η^μ favor an increased $d(x)/u(x)$ ratio at higher values of x than is predicted, as did the earlier DØ $W \to e\nu$ asymmetry measurement [20]. This is the most precise lepton charge asymmetry measurement from the Tevatron.

A. Huff, an undergraduate physics major, completed an analysis of the W asymmetry in the electron channel for her Honors Thesis with Blessing. Although this analysis will not be published, it contains most of the necessary elements, including electron efficiencies and charge misidentification probabilities in four regions of the detector. Her measurement is shown in Fig. 6.

2.4 H.B. Prosper (CMS)

Supersymmetry At the end of 2010, Prosper convened a team of experimentalists and theorists (Kraml, Pierini, Prosper, Sekmen and Spiropulu) to develop a research program to interpret LHC SUSY search results in terms of a broader class of SUSY models, specifically the 19-dimensional phenomenological Minimal Supersymmetric standard model (pMSSM) [22, 23]. He presented the scientific case for this program at a CMS SUSY group meeting in February 2011. The feasibility, and scientific utility, of this program was demonstrated in a paper he and his co-workers published in early 2012 [24]. This paper contains the first interpretation of LHC results within the context of the pMSSM. Figure 7 shows a result from this paper.

FSU graduate student Sam Bein joined the pMSSM effort and worked closely with Dr.

Lukas Vanelderen (University of Hamburg) to re-implement published CMS analyses in order to incorporate the results of these analyses in the our pMSSM work. The

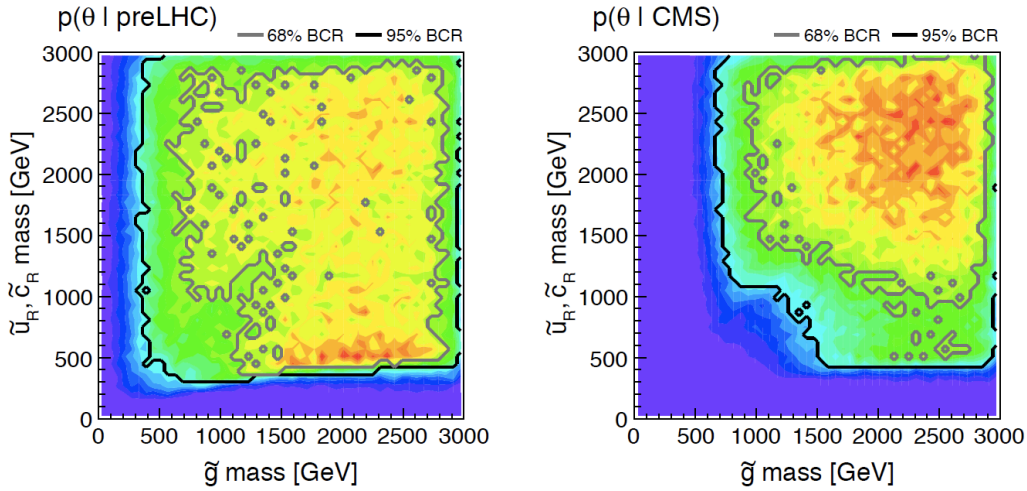

Figure 7: The left plot shows the allowed region in the squark mass/gluino mass plane of the pMSSM based on pre-LHC experimental results. The right plot shows what happens when CMS search results are included.

pMSSM research program has been actively pursued since 2011. Figure 8 shows a recent example of what has been learned about the gluino mass, presuming the pMSSM to be true. The parameter θ denotes generically a pMSSM parameter, such as the gluino mass $\tilde{m}_g$, and Z is a signed Bayesian measure of significance akin to the frequentist n-standard deviations. ($Z > 5$ corresponds approximately to the standard criterion for a discovery, while $Z < -1.65$ corresponds to a 95% exclusion.) Unlike the conclusions based on the use of highly constrained models, the one shown in Fig. 8 is more general in that it pertains not only to such models, but to the full MSSM for which the pMSSM is a good proxy. It would represent genuine progress if definitive statements could be made about the viability of the MSSM and its variants. Even after more than thirty years of theoretical and experimental investigation, we still do not know whether low-energy supersymmetry is a viable hypothesis.

Contact interactions Interactions characterized by a mass scale Λ too high to be probed directly at the LHC can be modeled as contact interactions (CI). The classic method to search for such interactions is to look for a distortion in the inclusive jet transverse momentum (p_{T}) spectrum at high p_{T} and low jet pseudo-rapidity (η). Prosper and former FSU graduate student Jeffrey Haas were the first to reprise this method in nearly twenty years. Their work was feasible because of the great progress that has been made in understanding parton distribution functions, the experimental

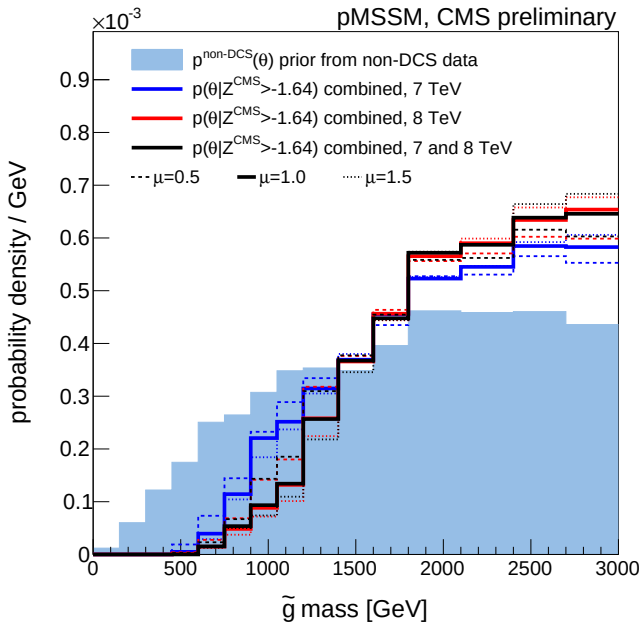

Figure 8: Posterior density of the gluino mass. The blue histogram is the prior density constructed from non-direct CMS search (non-DCS) data, while μ scales the SUSY cross section by $\pm 50\%$.

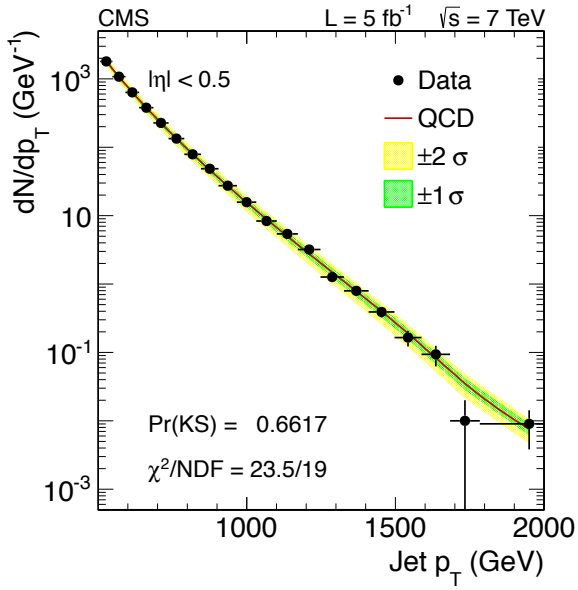

Figure 9: The observed inclusive jet transverse momentum spectrum compared with the QCD prediction at next-to-leading order convolved with the CMS jet energy response function.

jet energy scale, and the development of efficient and accurate methods, encoded in programs such as `fastNLO` [25], to compute jet observables.

The inclusive jet p_{T} spectrum measured by Prosper and Haas, based on the full 7 TeV CMS data set, is shown in Fig. 9. The results were published in the Physical Review [26]. We found that the scale of possible new interactions must exceed 9.9 TeV or 14.3 TeV at 95% C.L., assuming CI models with destructively or constructively interfering amplitudes, respectively. Jeffrey Haas graduated in 2013, shortly after the end of the grant period. Analysis of the 8 TeV CMS data set is in progress and it is expected that the work will continue into Run II of the LHC. But this work is contingent on further progress in reducing the uncertainties in parton distribution functions.

The Higgs boson The most significant advance during this grant period is clearly the discovery of the Higgs boson. FSU graduate student Joe Bochenek, together with Johnson and Prosper, in collaboration with Bhat (Fermilab) and De Filippis (INFN, Bari), worked on the search and discovery [27, 28] of the SM Higgs boson in the leptonic channels. This group focused on the search for the Higgs boson in the $H \to ZZ \to 4l$ channel [29] and developed the first comprehensive Bayesian analysis of this channel in CMS (and possibly at the LHC). Figure 10 shows the posterior density $P(m_H, \mu|D)$ from this analysis, where m_H is the Higgs boson mass

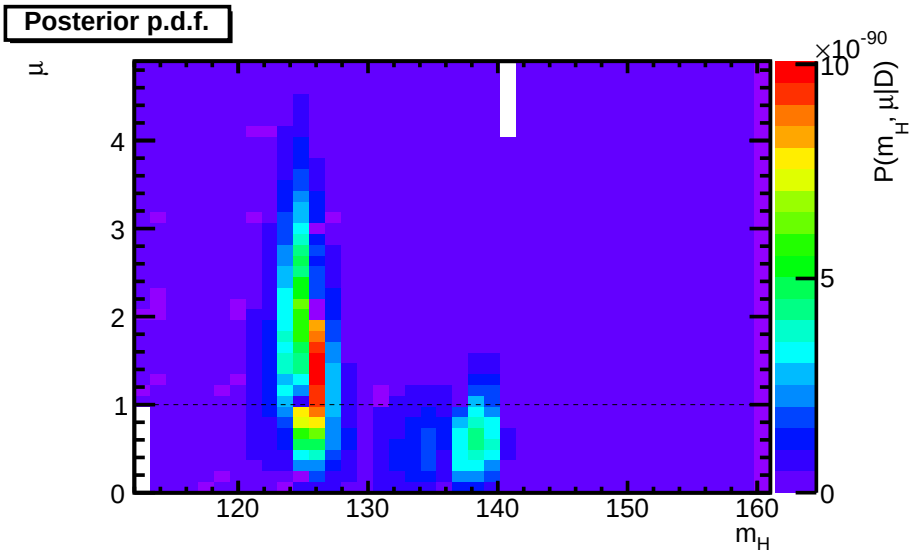

Figure 10: Posterior density, $P(m_H, \mu|D)$, of the Higgs boson mass m_H and signal strength modified $\mu = \sigma/\sigma_{\mathrm{SM}}$. These results accord with those shown on July 4th 2012 by ATLAS and CMS.

and $\mu = \sigma/\sigma_{\mathrm{SM}}$ is the Higgs boson production cross section σ relative to the standard

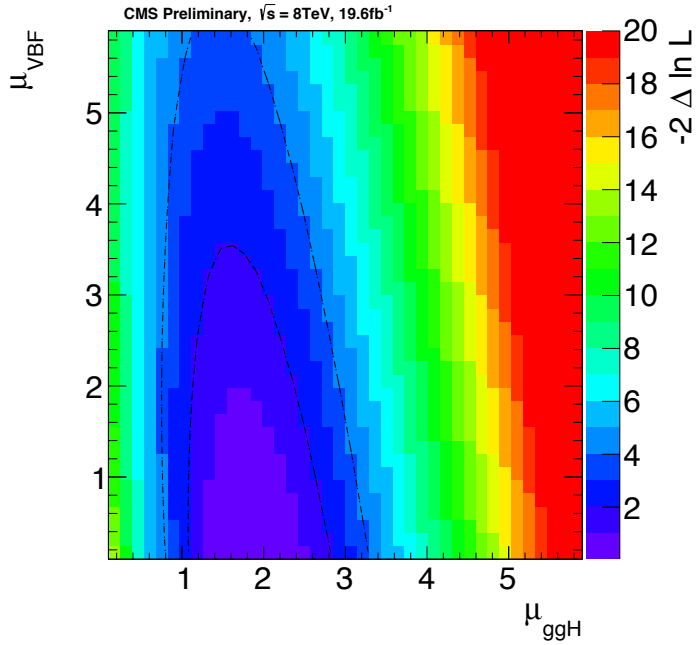

Figure 11: Posterior density of the vector boson fusion and gluon-gluon fusion signal strengths, $\mu_{\rm VBF}$ and $\mu_{\rm ggH}$, respectively.

model prediction, $\sigma_{\rm SM}$, and D denotes the (full 2011) dataset. A structure around 125 GeV is clearly visible, consistent with the results reported on July 4th, 2012 by CMS and ATLAS. We measure the Higgs boson mass to be $m_H = 125.7 \pm 0.5$ GeV, the Higgs-vector boson and fermion couplings to be $\kappa_V = 1.08 \pm 2.3$ and $\kappa_F = 1.3 \pm 0.5$, respectively, and we confirm that of several spin-parity hypotheses tested, the scalar, even parity hypothesis is preferred. Figure 11 shows the likelihood function for the vector boson fusion (VBF) and gluon-gluon (ggH) signal strengths $\mu_{\rm VBF}$ and $\mu_{\rm ggH}$, respectively, from which the coupling constants κ have been extracted.

2.5 H.D. Wahl (DØ)

QCD Physics In summer 2009, Bandurin, working with Professor Wahl, became co-convener of the DØ QCD Physics Group, whose principal interest was testing our understanding of quantum chromodynamics (QCD), e.g., jet production, jet properties, direct photon production, $W/Z + \gamma$ production, diffractive processes, as well as multiple parton interactions from a single $p\bar{p}$ collision. These processes are interesting not only because they allow a better understanding of QCD, but also because many of them are important backgrounds for other studies, in particular for Higgs physics and beyond the standard model searches.

Bandurin is a primary author of "Azimuthal Decorrelations and Multiple Parton Interactions in γ+2 Jet and γ+3 Jet Events in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV,"

published in Physical Review D [30]. Using inclusive samples of γ+2 jet and γ+3 jet events, the differential cross sections in the azimuthal angles between the γ+leading jet combination and an additional jet or two combined jets have been measured (Fig. 12).

The results indicate a significant contribution from multiple parton interaction (MPI) events and have been used to tune the MPI models. The γ+2 jet data are also used to determine the fraction of events with double parton (DP) interactions as a function of the azimuthal angle and the second jet p_T. Using γ+3 jet data, the fraction of events with triple parton interactions was estimated for the first time.

In parallel to this measurement, Bandurin estimated the background caused by DP events to associated WH production with $H \to b\bar{b}$ at the Tevatron. The DP rates are found to be much higher than the WH cross section. A set of variables to suppress the DP background was proposed by Bandurin *et al.* in JHEP [31].

Bandurin performed a new measurement of the $\gamma + b$-jet inclusive production cross section as a function of γ p_T, in two (central and forward) photon rapidity intervals and much wider than previous jet rapidity regions using the full DØ data set. Such measurements should provide information on the b quark PDFs from very small parton momentum fractions ($\approx$0.007) to very high (up to $\approx$0.4), i.e. in the region where b/c PDF uncertainties are significant. In addition to the QCD motivations, the knowledge of the heavy flavor PDFs is very important for understanding background events to many Higgs boson and new phenomena (e.g. technicolor $\omega_T \to \gamma\pi_T^0 \to \gamma b\bar{b}$ production) searches. While there is agreement between data and the NLO QCD predictions (calculated by Stavreva and Owens) for $\gamma + b + X$ production at $p_T^\gamma < 70$ GeV, there is disagreement between the theory and data for higher p_T^γ (Fig. 13). The measurement is published in Phys. Lett. B [32].

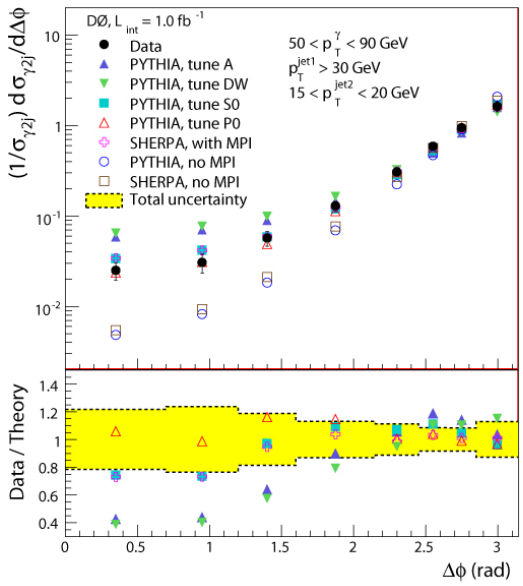

Figure 12: Normalized differential cross section in $\gamma + 2$ jet events in data compared to MC models and the ratio of data over theory, only for models including MPI, in the range $25 < p_T^{jet2} < 30$ GeV [30].

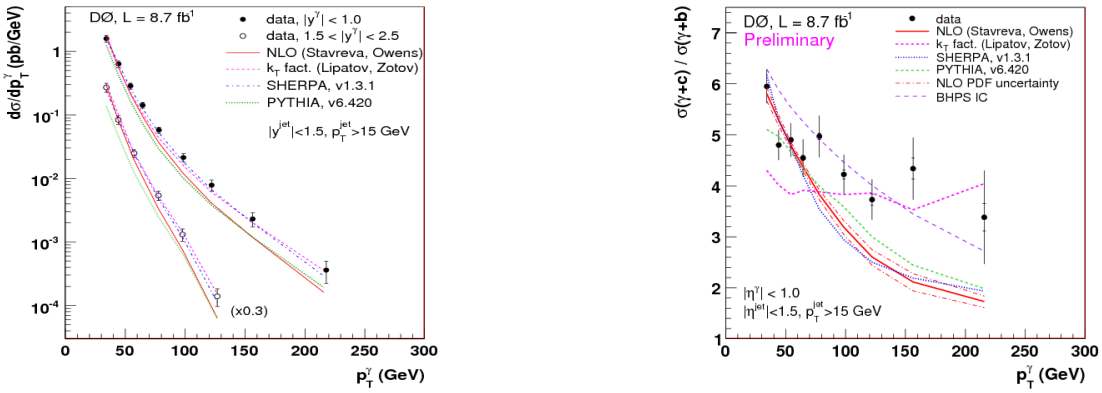

Figure 13: (left) The $\gamma + b$ production differential cross sections as a function of p_T^γ in the two photon rapidity regions, $|y^\gamma| < 1.0$ and $1.5 < |y^\gamma| < 2.5$ (multiplied by 0.3 for presentation). (right) The $\sigma(\gamma + c)/\sigma(\gamma + b)$ cross section ratio as a function of p_T^γ. The uncertainties on the points in data are the full experimental uncertainties. The measurements are compared to the NLO QCD calculations using CTEQ6.6M PDFs [33, 34] (solid line). The predictions from SHERPA, PYTHIA and the "k_T factorization" approach [35, 36] are shown by the dash-dotted, dotted, and dashed lines, respectively. NLO QCD predictions done with BHPS IC model [37, 38] are shown by the line with longer dashes.

3 Theoretical Physics Program

Senior Personnel: B. Berg, T. Okui, J. F. Owens, and L. Reina

Postdoctoral Associates: A. Jenkins (ended 8/31/2012), T. Schutzmeier (ended 5/15/2012), S. Quackenbush (started 9/1/2012), and P. Jaiswal (started 9/1/2012)

Graduate Students: H. Hartanto, S. Honeywell, K. Köpp, N. Sato, B. Thayer, D. Westmark, H. Wu, and C. Zeoli

This section covers the accomplishments of Senior Researchers Berg, Okui, Owens, and Reina for the period 1/1/2010 – 4/30/2013. This is not a comprehensive survey of all the work done. Rather we focus on the most important contributions while choosing topics that highlight the breadth and depth of the research activities.

3.1 B. Berg (Quantum Field Theory on the Lattice)

Deconfining phase transition. In RHIC we are dealing with an ensemble of volumes, with deconfined particles, with typical length scales of 5 to 10 fm. These "deconfined" volumes are not really small when compared with a characteristic correlation length set by the inverse deconfining temperature T_c. Hot deconfined regions are bordered by the cold confined phase. In order to simulate their influence, we modify the usual periodic boundary conditions (PBC) of lattice calculations to model a cold exterior. In an earlier pilot study of pure SU(3) lattice gauge theory (LGT) [39], Bazavov and Berg found for $L^3 \times L_t$ lattices in a range $L = 5-10$ fm up to 30% corrections to the transition temperature and width. This magnitude is comparable to the effects obtained by adding quarks. Consistency of our results with non-perturbative SU(3) renormalization group scaling indicated that they survive in the finite volume quantum continuum limit.

An overall factor to the lambda lattice scale Λ_L is the only free parameters in our SU(3) investigation, because Λ_L is determined by previous literature to be

$$a\,\Lambda_L = f_\lambda(\beta^g) = \lambda(g^2)\,\left(b_0\,g^2\right)^{-b_1/(2b_0^2)}\,e^{-1/(2b_0\,g^2)}\,, \tag{1}$$

where a is the lattice spacing, $b_0 = 11/(16\pi^2)$ and $b_1 = 102/(16\pi^2)^2$ follow from the renormalization group equation and, using results from [40], higher perturbative and non-perturbative corrections are parametrized [41] by $\lambda(g^2) = 1+\exp(\ln a_1 - a_2/g^2) + a_3\,g^2 + a_4\,g^4$ with $\ln a_1 = 18.08596$, $a_2 = 19.48099$, $a_3 = -0.03772473$, $a_4 = 0.5089052$ in better than 1% agreement with [42].

Though our physical observables in [39] show for $N_t = 4, 6$ scaling behavior with Λ_L defined by (1), one may be concerned because we simplified the confined exterior

phase to a strong coupling phase, which does not allow for a continuum limit. Would the correction possibly disappear as soon as the confined region allows also for a quantum continuum limit? We decided to address this problem also within pure SU(3) LGT and it became the Ph.D. project of Berg's graduate student Hao Wu.

To accommodate the confined outside as well as the deconfined inside phase in the SU(3) scaling region, we explore the geometry of a double-layered torus (DLT) [43] for which there appears to be no previous experience in LGT. PBC are used in the temporal direction. The boundary conditions (BCs) in the spacelike directions are so that one enters a second layer at the position where on would with PBC enter the same lattice from the other side again. After moving through the second layer, one reenters the first layer, and so on (the 2D topology is that of a Klein bottle). One layer is then kept in the deconfined phase and the other in the confined phase. A price paid for keeping both regions in the SU(3) scaling region is that we are limited to small temperature differences. To locate our deconfinement signals, maxima of the Polyakov loop susceptibility, with sufficient precision turned out to be very CPU intensive. Improved measurement procedures were of little avail and we ended up overcoming the problem by brute force computer time. We developed efficient Fortran MPI code, which was documented in Computer Physics Communications [44]. Receiving generous CPU time funding from DOE, considerable MC production was done at NERSC on their Cray XT4 and recently Cray XE6. Code development and very limited production was done on FSU PC clusters, which are also partially funded by DOE.

Preliminary results were reported at the Lattice 2011 conference [45] and reviewed to some extent in the plenary talk by Levkova [46]. We find substantial finite size corrections even for outside temperatures above 160 MeV, so that their existence can no longer be doubted for SU(3). Details of this work are included in recent publication [47].

U(1)⊗SU(2) and U(1) pure lattice gauge theory. In Ref. [48] a perturbatively non-renormalizable (pnr) gauge model with a local U(1)⊗SU(2) symmetry is investigated. It appears that there are only few studies of pnr models on the lattice. Our trust in perturbation theory suggests that the non-perturbative lattice approach will show that such models do not have a quantum continuum limit, what is true when there is no divergent correlation length. Somewhat surprisingly, the MC data of [48] favor a divergent correlation length defined by the inverse vector boson mass, though there is the usual limitation that the behavior cannot be followed all the way to the continuum limit.

A electroweak Lagrangian contains

$$\begin{aligned} \mathcal{L}^{\rm ew} &= -\frac{1}{2}{\rm Tr}\left(F^a_{\mu\nu}F^a_{\mu\nu}\right) - \frac{1}{2}{\rm Tr}\left(F^b_{\mu\nu}F^b_{\mu\nu}\right) \qquad (2)\\ &\quad +\overline{\psi}\left(i\gamma_\mu D^a_\mu - m\right)\psi + \overline{\psi}\left(i\gamma_\mu D^b_\mu - m\right)\psi\,, \\ D^a_\mu &= \partial_\mu + ig_a A_\mu\,, \quad D^b_\mu \;=\; \partial_\mu + ig_b B_\mu\,, \qquad (3) \end{aligned}$$

where A_μ are U(1) and B_μ are SU(2) gauge fields with the U(1) fields written as $A_\mu = 1_2\, a_\mu/2$ (1_2 is the 2×2 unit matrix), $F^a_{\mu\nu} = i[D^a_\mu, D^a_\mu]/g_a$, $F^b_{\mu\nu} = i[D^b_\mu, D^b_\mu]/g_b$. The Lagrangian (2) stays invariant when we transform both gauge fields under U(1)$\otimes$SU(2) instead with their usual gauge transformations. These *extended gauge transformation* should not be easily dismissed. They have attracted the attention of several initially very skeptical referees, who finally agreed to let their formulation in [48] pass. In essence one makes use of the widely ignored possibility (textbooks tend to claim the contrary) of local invariance without an interaction, which can be achieved by integrating over pure gauges as illustrated for free fields in [49].

While an explicit vector boson mass term breaks extended as well as usual gauge invariance, extended gauge transformation allow novel contributions to the Lagrangian (2) of which

$$-\frac{\lambda}{4}\,{\rm Tr}\left(F^{\rm add}_{\mu\nu}F^{\rm add}_{\mu\nu}\right)\;,\quad F^{\rm add}_{\mu\nu} \;=\; g_b\partial_\mu B_\nu - g_a\partial_\nu A_\mu + i\,g_a g_b\,[A_\mu, B_\nu]\;, \qquad (4)$$

has for the pure gauge part been investigated via LGT MC calculations. After fixing g_a in the Coulomb phase of compact U(1) and g_b in the scaling region of SU(2), one finds for small λ SU(2) observables in the confined phase. Increasing λ, the SU(2) center symmetry gets broken by a strong first order phase transition at some λ_c and for $\lambda > \lambda_c$ a massive vector boson is found from beautifully strong correlations in the spectrum of the deconfined phase. The U(1) photon stays massless in both phases (Mike Peskin raised questions about the possibility of a massless SU(2) vector boson, but this is ruled out by our MC data).

The identification of the massless photon poses problems in LGT and was done with the method of [50, 51] that relies on measuring the energy $E(\vec{k})$ of non-zero momentum states, estimating the mass via the lattice version of $m^2_\gamma = E^2_{\vec{k}} - \vec{k}^2$, where $E_{\vec{k}}$ is the energy from "cosh" fits of correlation functions. Beyond the earlier papers our calculations revealed a finite size behavior with negative m^2_γ values on small lattices, which together with the behavior for a free scalar field was further studied in [52] by Berg with McDargh an undergraduate student student supported by the HEP group[1],

A surprise from the free field calculation is that the corrections become larger when the correlation length $\xi = m^{-1}$ decreases as follows from the derived exact equation $E_{\vec{k}} = \cosh^{-1}(1 + m^2_{\rm eff}/2)$, $m^2_{\rm eff} = m^2 + 4\sum_{i=1}^{d-1}\sin(k_i/2)^2$, where m is the mass parameter of the free scalar lattice action.

[1]In fall 2012 McDargh accepted a TA offer by the Carnegie Mellon University and intends to work as graduate student with Colin Morningstar.

Classically, the addition (4) can be mapped on pure U(1) and SU(2) Lagrangians, which are usually obtained by integrating over gauge transformations with Gaussian weighting functions, Eqn. (9.56) and (16.34) of Ref. [53], where (16.34) comes now without the Faddeev-Popov ghost fields. Therefore, divergent integrals are left over, which render the model pnr and transitions into longitudinal modes violate unitarity already in the tree approximation. If our observed vector boson mass corresponds to counterterms that are divergent beyond perturbative theory, one expects in the non-perturbative lattice regularization that the model does not allow for a a second order phase transition $a/\xi \to 0$, where the correlation length ξ is defined by the inverse vector boson mass $\xi = 1/m_W$. However, our MC calculations [48] favor a second order phase transition for a suitably chosen $\lambda \to \infty$ approach. Consequently, a quantum continuum limit appears possible and leaves us with open theoretical questions that warrant further investigations independently of the fact that the Higgs boson now appears firmly established [27, 28]. Quoting from one of the referee reports:

> "In this second report on this paper, I recommend that it be accepted for publication in Physical Review Letters. The author has not answered all relevant questions, but the material is interesting enough that it deserves publication. ...
>
> Is the model described a Euclidean representation of a unitary quantum field theory? We believe the answer is yes, because it has a reflection-positive action. So the apparent violation of unitarity in perturbation theory has to be repaired somehow. It will be interesting to find out exactly how this works. One possibility is that the theory generates some new bosons, either non-perturbatively or by a rewriting of the theory visible in perturbation theory, and these play a role in the unitarity sum over physical states."

Some of our physics questions loosely related to this line of research may be addressed within compact U(1) LGT and, perhaps, in some toy models, which can provide convenient simplifications while still catching the essence of a problem. In this spirit U(1) LGT was introduced in the groundbreaking paper by Wilson [54]. Surprisingly, even by itself it still poses challenges. On the lattice this system undergoes a phase transition, which one expects in the finite temperature geometry to be either first order or in the universality class of the 3D XY model. Instead, our earlier finite size scaling estimates of critical exponents are consistent with the 3D Gaussian fixed point [55]. As it is unstable, the estimates must turn around for larger lattices, or belong to a close-by new, non-trivial fixed point, which would be of importance for renormalization group theory. We performed a calculation of the density of states and Fisher zeros for U(1) LGT in [56], which covers concepts that are of general importance for the thermodynamics of statistical systems. However, these calculations underlined again that larger lattices are needed for seminal results. Massively parallel computing should allow for that and such an investigation could be subject of a Ph.D. dissertation. The discovery of the Higgs boson at the LHC and measurements

of its properties, which are all consistent with standard model predictions, has caused a tabling of this project. However, there are almost no studies of non-perturbative field theories on the lattice and it is of theoretical interest to understand better how divergent perturbative counterterms manifest themselves in a non-perturbative LGT simulation. With this in mind, it may be of interest to return to simulations of the model and accompany such work by perturbative calculations.

Algorithms and statistical methods. Algorithms and statistical methods often provide the technical foundation of our research and their development is, therefore, an integral part of it. The second edition of Berg's book [57] is being prepared, including updates of the extensive Fortran code that comes with the book. McDargh has tested updated code for several Fortran 90 compilers (gnu, Portland group, Intel). The second edition of the book adds about 120 pages, including a new LGT chapter. There is a significant extension of the present coverage of parallel computing by extracting pedagogical MPI checkerboard code from software developed for our research [44].

3.2 T. Okui (Physics Beyond the Standard Model)

Theory and LHC Phenomenology of Vectorlike Confinement In collaboration with C. Kilic (Rutgers) and R. Sundrum (Maryland), Okui argued in Ref. [1] for the plausibility of a broad class of theories at the TeV scale consisting of a new QCD-like strong interaction and new quark-like fermions that interact via the new strong interaction. Unlike standard model (SM) quarks, the new "quarks" are assumed to be vectorlike (i.e., non-chiral) under the electroweak interactions. It was found that, when these new vectorlike quarks get confined at the TeV scale (i.e., "vectorlike confinement"), the "hadrons" of the new strong dynamics exhibit an extremely rich phenomenology at the LHC, while having negligible impact on precision electroweak and flavor observables. It was pointed out that spin-1 bound states that are analogous to the ρ mesons of QCD can be resonantly produced at the LHC, and these resonances will promptly decay to lighter spin-0 bound states that are analogous to QCD pions. Some of these spin-0 bound states are like the π^0 and will promptly decay to a pair of SM gauge bosons, while others are stable on the collider time scale like $\pi^\pm$ or K mesons. Okui and co-workers identified a diverse set of final states with little SM background, including multiple photons/Ws/Zs, missing energy, charged massive stable particles (CHAMPs), bound states of massive stable colored particles (R-hadrons) and the possibility of highly displaced vertices in dilepton, leptoquark or diquark decays. An interesting highlight was a novel experimental signature of resonance reconstruction out of CHAMP pairs (di-CHAMP resonances) and R-hadron pairs (di-R-hadron resonances).

In a subsequent paper [11] with C. Kilic, Okui investigated in detail the LHC phenomenology of the vectorlike confinement scenario. In particular, he and his colleagues focused on the phenomenology of the di-CHAMP and di-R-hadron resonances as well as the multi-photon/W/Z signals. By performing detailed simulations, they showed that a full reconstruction of the spectrum is possible, which would provide powerful evidence for the underlying vectorlike confinement dynamics.

Viable, Flavor/CP Safe Model of Gravity Mediated Supersymmetry Breaking In collaboration with G. Kribs (Oregon) and T. Roy (Washington, Seattle), Okui presented in Ref. [11] a complete, viable model of gravity-mediated supersymmetry breaking that is safe from all flavor constraints. The central new idea of the construction was first, the use of a supersymmetry breaking sector without any gauge singlets but with D-term supersymmetry breaking comparable to the F-term, causing supersymmetry breaking to be dominantly transmitted through $U(1)_R$-symmetric operators to the visible sector; second, the engineering of the visible sector such that an accidental $U(1)_R$ symmetry emerges naturally. The resulting gauginos are Dirac fermions, not Majorana, unlike the gauginos in the conventional supersymmetric extensions of the SM, and it was found that the Dirac gaugino masses are naturally driven to larger values by renormalization group evolution. Even though gravity mediation gives flavor-violating soft masses to the scalar supersymmetric partners of SM quarks and leptons, the accidental $U(1)_R$ symmetry together with the large gaugino masses greatly suppresses all flavor violation constraints in the Kribs-Roy-Okui model. Okui and co-workers have argued that the realization of the accidental $U(1)_R$ requires the introduction of a new gauged $U(1)_X$ symmetry that is spontaneously broken with electroweak symmetry breaking. The massive gauge boson associated with this $U(1)_X$ has very peculiar couplings — it has $\mathcal{O}(1)$ strength to the Higgs fields but only has tiny $\mathcal{O}(10^{-3})$ strength to the lepton and quark fields. Thus, this $U(1)_X$ gauge boson can be remarkably light and have a significant discovery potential at the LHC.

LHC Implications of WIMP Dark Matter and Gauge Coupling Unification In collaboration with C. Kilic (Rutgers), Okui and his student K. Köpp investigated in Ref. [58] the LHC implications of the assumptions that dark matter consists of a weakly interacting massive particle (WIMP) and that the three gauge couplings unify at some high scale, in the context of non-supersymmetric field theories. They identified robust phenomenological trends of possible matter content at the TeV scale. In particular, within the LHC reach, there should be new colored particles with Yukawa couplings, λ, to quarks and the Higgs. Okui and co-workers investigated the collider signatures that are characteristic of all such models. The λ couplings are constrained by flavor/CP physics and in the largest portion of the allowed parameter space the new colored particles are stable on collider time scales, hence appearing as R-hadrons. The range of the R-hadron mass was identified for which there was a potential for discovery at the early LHC ($\sqrt{s} = 7$ TeV, 1 fb^{-1}). Flavor/CP constraints also allow

a sizable range of λ where the new colored particles decay promptly, providing a new Higgs production channel with a cross-section governed by the strong interaction. The case of $h \to WW$ was studied by Okui and co-workers who showed that it is possible for the Higgs production from this new channel to be discovered before that from the standard model at the LHC.

A Unified, Flavor Symmetric Explanation for the t-$\bar{t}$ Asymmetry and Wjj Excess at CDF In collaboration with A. Nelson and T. Roy (Washington, Seattle), Okui presented in Ref. [59] a simple, perturbative, and renormalizable model with a flavor symmetry which can explain both the t-$\bar{t}$ forward-backward asymmetry and the bump feature present in the dijet mass distribution of the Wjj sample in the range 120–160 GeV that was recently reported by the CDF collaboration. The flavor symmetry introduced not only ensures the flavor/CP safety of the model, but also relates the two anomalies unambiguously. It also predicts a comparable forward-backward asymmetry in c-$\bar{c}$, while the forward-backward asymmetry in b-$\bar{b}$ should be small. It was found that a bump in the dijet mass distribution in Zjj sample is also predicted by the flavor symmetry but with a suppressed cross-section. The structure of the Nelson-Roy-Okui model is very tight, with only one mass and one coupling that are relevant for those two signals, and thus can be readily tested unambiguously at the LHC.

The Hierarchy Problem in the Multiverse In collaboration with G. Perez and O. Gedalia (the Weizmann Institute of Science, Israel), Jenkins worked on understanding what the string-theory landscape and the eternally-inflating multiverse might imply for expectations of the discovery of new particles and interactions at the LHC. In particular, it is argued in Ref. [60] that (contrary to the arguments of other theorists), the lightness of the Higgs boson with respect to the Planck scale of quantum gravity is not explicable in terms of an "anthropic" requirement for the existence of light fermions.

Their argument is based on two principal observations. First, the flavor hierarchy puzzle (reflected in the smallness of the Jarlskog determinant ($\sim 10^{-22}$) suggests that some flavor dynamics must be invoked in order to generate that hierarchy naturally. This hierarchy cannot be resolved by invoking the anthropic principle, since it concerns the masses and mixings of heavy quarks that play no role in any of the processes connected with the evolution of life as we know it. Motivated by this, a general parametrization is chosen of the distribution of Yukawa couplings that fits with most of the models of flavor dynamics that have been proposed so far in the theoretical literature during the last thirty years (including Frogatt-Nielsen models, partial compositeness, and extra dimensions with split fermions models).

It is then argued that it is likely that the Yukawa couplings of the standard model would scan over the multiverse, under the reasonable assumption that dimensional parameters may scan. This leads to the surprising conclusion that universes with

light fermions but no observable weak interaction should be extremely common. Since those universes have no obvious obstruction to the evolution of organic life, the fact that we live in a universe with a measurable weak interaction would be an unexplained rare event. This strongly suggests that some new physics (such as low-energy SUSY or technicolor), discoverable at the LHC, is needed to stabilize the Higgs mass scale in the landscape.

Gyroscopic Inflation Besides collider experiments, cosmological observations offer powerful and complementary probes into the nature of fundamental particles and interactions. Cosmology provides experimental evidence that the SM must be extended to accommodate a dark matter candidate particle and a mechanism to generate baryon asymmetry. Moreover, the spectacular data from the CMB and large-scale structure measurements, notably from WMAP, SDSS, and now Planck, have firmly established slow-roll inflation as the source of primordial density fluctuations, requiring the SM to be extended further by a mechanism for inflation. Okui has therefore investigated models of inflation that make predictions that are testable in the near future.

A challenging problem of slow-roll inflation from the viewpoint of effective field theory is the difficulty of protecting its extremely flat potential against quantum corrections. This problem appears robust, as extreme flatness is required to maintain inflation for a sufficiently long time, while the loop corrections can be ultimately attributed to the need for eventually ending the inflation. While an exactly flat potential could be ensured by imposing a shift symmetry $\psi \to \psi + c$ for the slow-roll field ψ, it seems that the shift symmetry must be violated because ending inflation requires the potential to drop to zero at some point. With his postdoc, Alejandro Jenkins, Okui proposed a new framework, "gyroscopic inflation" [61], which provides a simple counterexample to this seemingly reasonable argument.

The essence of gyroscopic inflation can be neatly captured by drawing an analogy with a spinning symmetric top in classical mechanics. A top spinning rapidly on a nearly frictionless table can stay upright for a long time, maintaining an approximately constant potential energy, until the spinning eventually slows and the top falls down, causing the potential energy to drop to zero. Such a trajectory of potential energy is exactly what we need for a successful slow-roll inflation. Here, the two Euler angles ϕ and ψ (the top's precession and spinning) are cyclic, thus obeying exact shift symmetries, while the third angle θ (the top's tilt) carries the potential energy of the whole system. Therefore, in Ref. [61], ψ is promoted to a slow-roll field, equipped with a shift symmetry leading to a flat potential, and θ to a "waterfall" field (borrowing the terminology of hybrid inflation [62]), which has a potential. The key novel feature here is that the stability of the waterfall field θ (or the top's tilt) is controlled by the *derivative* of the inflaton ψ (or how fast the top is spinning), not by ψ itself. Therefore, ending inflation does not require violating the shift symmetry for ψ, contrary to the usual expectation. Gyroscopic inflation simply ends when the

Hubble friction due to the expansion of the universe decreases the value of $\dot{\psi}$ below some threshold value.

In Ref. [61], Jenkins and Okui identified the simplest relativistic field theory of ψ and θ that features the above properties. The theory is weakly coupled and well controlled as an effective field theory, and is therefore used to demonstrate explicitly that gyroscopic inflation can indeed be robustly protected against quantum corrections. This minimal gyroscopic model also predicts $r \ll 3 \times 10^{-2}$ for the tensor-to-scalar ratio r for primordial perturbations. (Detection of primordial gravitational waves may be within reach of the next generation of CMB experiments, $r \gtrsim \mathcal{O}(10^{-2})$.) This prediction should be compared to that of the simplest inflation model of all, namely, the $m^2\psi^2$ model of chaotic inflation [63], which is essentially the minimal gyroscopic model without the θ field. This model predicts $r = 0.13$, while the Planck Collaboration reports an upper limit of 0.13 [64]. Modifying the chaotic inflation prediction of r would require introducing a second field that dominates the inflationary potential energy. Preserving the shift symmetry would then necessarily lead to gyroscopic inflation.

Like hybrid inflation [62], however, the minimal gyroscopic model has a tension in $n_{\rm s}$, the tilt of the scalar power spectrum. The current constraint is $1 - n_{\rm s} = 0.040 \pm 0.007$ (68% C.L.) from Planck [64], while the minimal gyroscopic model predicts $1 - n_{\rm s} < 0$, although $1 - n_{\rm s}$ can be easily made as small as $\approx 10^{-3}$. Hence, the tension is nontrivial but perhaps not so severe as to exclude the model.

CP Violation in the Higgs Sector While the discovery of a Higgs boson in 2012 is a triumph of the SM, overwhelming evidence exists for new physics. The study of CP violation is particularly well motivated, as it could give clues to the origin of the large matter-antimatter asymmetry present in the universe. The recently discovered Higgs boson provides a new territory to search for additional CP violation. In Ref. [65], in collaboration with R. Harnik *et al.*, Okui proposed a novel observable Θ that can be used to measure the CP phase in the $h\tau\tau$ Yukawa coupling. Currently, this CP angle is allowed to be anywhere between 0° (CP even) and 90° (CP odd) by all existing data, including the null results in the search for the electron's electric dipole moment. If the phase turns out to be 0°, it will be a further confirmation of the SM, while any nonzero angle will be an evidence for physics beyond it at the TeV energy scale. Since the study performed in Ref. [65] was at parton level, a crucial question is: how well does the Θ variable fair once realistic instrumental effects of the LHC detectors are taken into account? A paper answering this question has been submitted for publication.

3.3 J.F. Owens (QCD Studies of Large Momentum Transfer Processes)

CTEQ Activities Owens is a founding member of the CTEQ Collaboration[2] a group of theorists and experimentalists from many universities and laboratories. The goal of the collaboration is to further the quantitative comparison of theory and data for standard model processes. CTEQ-related activities include the ongoing global fitting activities for the determination of parton distribution functions, planning for the annual summer school, and the sponsoring of various workshops.

CTEQ activities during the past three years include:

1. 2010 Summer School in Lauterbad, Germany (joint with MCNET)
2. Workshop on "Standard Model Benchmarks at the Tevatron and LHC", November 19-20, 2010, Fermilab
3. 2012 Summer School in Lima, Peru
4. 2013 Summer School at the University of Pittsburgh

Owens participated in the planning and running of the 2012 Summer School and the planning for the 2013 Summer School. He presented a lecture on direct photon production at the 2012 Summer School.

Parton Distribution Functions Owens significantly updated and extended his own fitting and evolution package as follows:

- Added PDF error routines
- Added new routines to allow one to fit either DIS cross sections or structure functions
- Added the ability to fit high Q^2 HERA neutral current data, keeping both the photon and Z exchange contributions
- Added a charged current cross section routine to handle the HERA charged current data
- Wrote a next-to-leading-order (NLO) routine for photon plus jet production as measured by the DØ Collaboration
- Wrote an NLO subroutine to calculate the W and Z production cross sections

[2] http://www.cteq.org

- In collaboration with Wally Melnichouk and Alberto Accardi from Jefferson Lab, incorporated higher twist contributions, target mass corrections, and nuclear corrections for deuterium targets
- Added NNLO evolution
- Interfaced the fitting package with the program fastNLO in order to speed up the fitting of jet data at NLO without resorting to K-factors
- Added the option to fit the Z rapidity distribution at NLO

This updated and enhanced program package has been used for studying the role of nuclear corrections when using deuteron targets. This collaborative work involves CTEQ members (Owens, Morfín, and Keppel) as well as Jefferson Lab and Hampton University researchers. This CTEQ-Jefferson Lab Collaboration is referred to as the CJ Collaboration. The following is a summary of the work of this collaboration.

Global fits for parton distribution functions (PDFs) have traditionally focused on using data in kinematic regions where one could safely ignore non-leading contributions such as higher-twist terms and target mass corrections in deep inelastic scattering. In this case, cuts such as $Q > 2$ GeV and $W > 3.5$ GeV have been used. This has the effect of removing data for $x > 0.7$ except at very high values of Q^2 where the data become statistically limited. As a result, our knowledge of high-x PDFs is rather limited. The PDFs are constrained in this region by the enforcement of momentum conservation and quantum number sum rules. Furthermore, the evolution equations cause the PDFs at high values of x and low values of Q^2 to feed down to lower values of x and higher values of Q^2. But it would be best if one were able to confront data directly in the large-x region. To do so, however, would require lowering the cut on W. Interpreting the data in this extended region would require the inclusion of both higher twist terms and target mass corrections.

The first analysis of this collaboration, described in Ref. [66], found the following.

1. Stable leading twist PDFs can be reliably extracted in with cuts as low as $Q^2 > 1.69$ GeV^2 and $W^2 > 3$ GeV^2 provided that both higher twist terms and target mass corrections are included. Different models for the target mass corrections yield different higher twist parameters, but the leading twist PDFs show little variation.
2. Nuclear smearing corrections for deuterium targets significantly affect the d-quark PDF while the u-quark PDF in the large-x region shows less dependence, being well constrained by the proton target data.
3. The resulting d-quark PDF is reduced at large values of x relative to the extrapolations of previous fits which were done with higher cuts and, hence, were only directly sensitive to the region $x < .7$.

The second phase of this project involved a more detailed investigation of the uncertainties induced by variations in the models used for the nuclear corrections. It was found that, contrary to conventional wisdom, the nuclear corrections for deuterium could affect PDFs to values of x as low as 0.5. It is important to realize that the u PDF is well constrained by proton DIS data, so the main effect of the nuclear corrections is to modify the d PDF. However, there is an anticorrelation between the d and gluon PDFs which is caused by the collider jet data - if the d PDF is reduced the difference is made up by the gluon, since the u PDF is already well constrained. These results were published in the Physical Review [67].

Three sets of PDF parametrizations that span the range of possible nuclear corrections have been developed and can be easily accessed through a simple user interface. PDF errors have been treated in the conventional way by providing "PDF error sets" based on the Hessian method. These PDFs are being referred to as the CJ PDF sets, with CJ denoting CTEQ-Jefferson Lab.

With the initial CJ PDF sets finalized, it is now possible to assess the effects of new data as they become available. One project is to consider the constraints on the strange quark that come from considering the $W^{\pm}$ and Z^0 rapidity distribution data from ATLAS and CMS. Such an analysis has been carried out by the ATLAS Collaboration [68]. It will be of interest to see the effects of such an approach in a full global fit. Previously, global fits have relied on neutrino data to constrain the strange quark, but this requires knowledge of the appropriate nuclear corrections.

Resummation and PDF Fits In the previous discussion it was pointed out how the uncertainties introduced by variations in the nuclear corrections used for deuterium targets can induce additional uncertainties in the gluon distribution. One would like to have observables which directly constrain the gluon PDF. It was long thought that such a process would be high-p_T direct photon production. Collider experiments are generally sensitive to the gluon PDF at relatively low values of x due to the high center-of-mass energy. Conversely, fixed target experiments can probe the large-x region. Data from the ISR, RHIC, CERN SPS Collider, the Tevatron, and the LHC are generally in good agreement with QCD predictions apart from some disagreements at the low-p_T end of the spectra. Unfortunately, the situation is not so clear when the fixed target experiments are included. Some of this is due to disagreements between experiments (although the corresponding kinematic regions do not quite overlap) and some is due to incomplete calculations. NLO calculations for the direct and fragmentation components are standard. Moreover, investigations of soft gluon (or threshold) resummation for the direct part have shown that these corrections are small. However, de Florian and Vogelsang [69] demonstrated that the threshold corrections for the fragmentation component at fixed target energies can be quite substantial. This is due to the fact that kinematically the fragmentation photon is biased towards taking a large fraction z of the parent parton's momentum and the threshold corrections sum large factors of $\ln(1-z)$. This observation holds the key

to providing a unified description of direct photon data over an extended range of energies which includes the fixed target region. Such a description could enable direct photon data to be used in global fits in order to help constrain the gluon PDF.

One of Owen's students, Nobuo Sato, wrote a program that calculates direct photon production to NLO accuracy and which also includes threshold resummation. Sato investigated the extent to which the threshold resummation corrections allow one to have a unified description of direct photon production.

DIS and lepton pair production data both play significant roles in the global fits for PDFs. Threshold resummation effects in DIS can be large as $x \to 1$. In lepton pair production the threshold resummation corrections are large near the partonic threshold and these corrections can be large over an extended range in x_F, the scaled longitudinal momentum of the lepton pair. The region of large x_F is important in constraining the large-x PDFs. Therefore, it is quite possible that the PDFs obtained in global fits might be altered if threshold resummation effects are included. One of Owen's students, David Westmark, has written programs for lepton pair production and DIS to NLO accuracy which also include threshold resummation corrections. He is investigating the extent to which these corrections will modify the PDFs resulting from global fits.

γ + Heavy Quark Production Owens continued to work with his former student, Tzvetalina Stavreva. He assisted with predictions for γ+heavy quark production predictions for heavy ion experiments. This process is sensitive to the gluon distribution as the heavy quark parton distribution functions are driven by gluons splitting into quark-antiquark pairs. The process may provide a good probe of the nuclear modifications of the gluon PDF in heavy nuclei. This work, which has been published in Ref. [70], is an extension of the NLO calculation done by Tzvetalina for her dissertation and which was published in Ref. [71].

Neutrino Nucleus Interactions Owing to the weak interaction of neutrinos with matter, neutrino experiments rely on the use of heavy targets such as iron or tungsten in order to achieve high interaction rates. Therefore, in comparing data with predictions, it is necessary to use nuclear PDFs rather than proton PDFs. If a first principles method for relating nuclear and nucleon PDFs existed, then this would not be a problem. However, to date, only models are available for making this connection. Accordingly, it is interesting to examine whether or not the nuclear PDFs are universal. In Ref. [72] it was shown that it was difficult to incorporate the high statistics NuTeV neutrino results in global fits using modern estimates of the nuclear corrections. Furthermore, a series of papers [73, 74, 75] compared the iron PDFs one gets directly from the NuTeV experiment with nuclear PDFs obtained using charged lepton DIS. These latter studies have been done by a collaboration that includes several CTEQ members (Keppel, Morfín, Olness, and Owens), and researchers from Grenoble and Karlsruhe. The collaborative effort, which has resulted in sets of nuclear PDFs,

is referred to as the nCTEQ Collaboration. One goal of nCTEQ is comparing the A-dependence from CHORUS, NuTeV, and NOMAD with that obtained using charged lepton-nucleus DIS. This is an important topic since neutrino experiments are key to flavor differentiation amongst the various PDFs. Indeed, the NuTeV dilepton data are the only available source for constraining $s - \overline{s}$, yet there are uncertainties due to nuclear effects.

In Ref. [74] the nuclear correction factors F_2^A/F_2^N were studied separately for both charged lepton and neutrino DIS. A number of differences were noted, including the apparent lack of a shadowing region in the neutrino case as well a decrease in the nuclear correction at large values of x for neutrinos as opposed to charged leptons. A follow-up analysis reported in Ref. [75] quantified these observations by including both types of data in a global fit. Weights were introduced in the χ^2 definition so that one could emphasize one type of data or the other. When correlated errors were taken into account it was found that one could not obtain simultaneous good descriptions of both types of data using the same A-dependent parametrizations for the nuclear PDFs, a conclusion dominated by the high-statistics NuTeV data.

3.4 L. Reina (Higher Order QCD Studies for Background Processes and Higgs Boson Production at Hadron Colliders)

During the past three years Reina has worked on several projects pertaining to higher order QCD corrections to Higgs and weak gauge boson production modes with heavy quarks at hadron colliders, as well as the development of broad impact techniques for higher order calculations in quantum field theory. This work was done in collaboration with students H. Hartanto, P. Rottmann, and B. Thayer, postdoc T. Schutzmeier, as well as collaborators at other institutions.

Schutzmeier joined the group in January 2009 as a postdoc and continued his appointment until fall 2012. Hartanto joined the group in summer 2008, and graduated in 2012. He was awarded a Fermilab Fellowship in Theoretical Physics that supported him for one year, starting in fall 2011, to work at Fermilab under the supervision of John Campbell. Thayer joined the group in 2007 and graduated in 2012. In 2009, Thayer was awarded a LHC-Theory Initiative Graduate Fellowship (funded by the NSF) that covered his salary, tuition fees, travel, and equipment expenses from summer 2009 through spring 2010. Finally, Rottmann joined the group in 2006 and received his Ph.D. in spring 2011.

Reina gave several national and international talks, and taught at several summer schools, including invited talks on *Higgs Physics* at the 2011 Winter Aspen Meetings and the 2011 ILC meeting (Eugene, OR), an invited talk on *Interpreting Collider Data* at the 2011 APS meeting, as well as lectures at TASI 2011 (Boulder, CO) and the CTEQ Summer School (Madison, WI).

Since January 2010 Reina has served as theory convener of the $t\bar{t}H$ subgroup of the "*LHC Higgs cross section working group*" and has actively contributed to the progress of the workshop and to the organization of several meetings (three in 2010 and two in 2011). In May-June 2010 she was a guest of the Aspen Center for Physics for two weeks. In June-July 2011 she was a guest of the Kavli Institute for Theoretical Physics (Santa Barbara). Finally, during the past two years, two of Reina's former students have obtained Assistant Professor positions: Chris Jackson at the University of Texas at Arlington (after postdoc positions at BNL and ANL), and Fernando Febres Cordero at the University Simon Bolivar, in Caracas, Venezuela (after a postdoc position at UCLA).

The scientific activity of the group for the past three years is described in the following.

Weak Gauge Boson Production with Bottom Quarks ($Wb\bar{b}/Zb\bar{b}$, Wb/Zb) (Reina and Schutzmeier) Most signals of new physics at hadron colliders involve a weak vector boson (W, Z) plus jets containing heavy quarks (c, b). For example, at the Tevatron, both $Wb\bar{b}$ and $Zb\bar{b}$ production modes are major backgrounds for Higgs boson production via associated production with W/Z bosons ($p\bar{p} \to WH$ and $p\bar{p} \to ZH$), and, in the case of $Wb\bar{b}$, single-top production ($p\bar{p} \to t\bar{b}, \bar{t}b$). This is also true at the LHC, where, however, other modes and measurements are even more important. For instance, $Zb\bar{b}$ is one of the major backgrounds for a Higgs boson decaying into ZZ pairs, when one of the Z bosons decays leptonically and the other hadronically. Moreover, measuring $Z + 1b$ jet production gives a direct handle on the b-quark parton distribution function, reducing the theoretical uncertainty that currently affects the prediction for $H + b$-jets production. The above considerations motivate the considerable effort needed to produce precise theoretical predictions of both $Wb\bar{b}$ and $Zb\bar{b}$ production for the Tevatron and the LHC, especially for the latter now that the Tevatron era is over. Indeed, this has been a very active and productive field of research for Reina's group.

Reina, in collaboration with F. Febres Cordero (UCLA and USB-Caracas) and D. Wackeroth (SUNY, Buffalo) completed a study of $Wb\bar{b}$ and $Zb\bar{b}$ production at both the Tevatron [76] and the LHC [77], which includes full NLO QCD effects and full non-zero b-quark mass effects. Moreover, Reina, F. Febres Cordero, and D. Wackeroth, in collaboration with J. Campbell and R. K. Ellis (Fermilab), F. Maltoni (Louvain U.), and S. Willenbrock (Illinois U., Urbana), have combined the results of their NLO QCD calculation of $Wb\bar{b}$ production [Phys. Rev. D74, 034007 (2006) and Ref. [77]] with the NLO calculation of Wbj production [Campbell et al., Phys. Rev. D75 054015 (2007)] to provide the first NLO calculation of W production with at least one b jet at hadron colliders, including the effects of a the b-quark mass [78]. This new result has made possible a state of the art comparison with the experimental measurement of W production with at least one b jet, which is currently a fundamental part of the program of CDF, DØ, ATLAS, and CMS, because of its relevance to Higgs boson searches and measurements.

Given the utility of interfacing the NLO QCD parton level calculation for $Wb\bar{b}$ and $Zb\bar{b}$ with a NLO parton shower Monte Carlo program, Reina collaborated with C. Oleari (University of Milan-Bicocca) to interface her $Wb\bar{b}$ and $Zb\bar{b}$ NLO calculations with `Pythia` and `Herwig` using the `POWHEG` method (of which C. Oleari is one of the authors). Results for $Wb\bar{b}$ appeared in Ref. [79], while results for $Zb\bar{b}$ will appear soon. The interface has presented several interesting challenges since it is the first high multiplicity massive process to be implemented in a NLO Monte Carlo program.

A major project was completed by Reina and Schutzmeier, which consists of the calculation of $W + b + j$ and $W + 2b + j$ at NLO in QCD, within a fixed flavor scheme, i.e., with a massive b quark. This project entailed the calculation of both $q\bar{q}' \to Wb\bar{b}+g$ and $qg \to Wb\bar{b}+q'$ at NLO in QCD. Since the last process is responsible for the large scale uncertainty of the NLO prediction for $W + b$ jets at the LHC, the new results should help stabilize the theoretical predictions. The first results for the one-loop corrections to these $2 \to 4$ processes have been published in Ref. [80] and are being implemented in a full-fledged study of the properties of the NLO predictions for $W + b$ jets at both the Tevatron and the LHC.

Given the high multiplicity of particles involved ($2 \to 4$ processes at tree level), the calculation, including massive b quark effects, is at the cutting edge of current NLO QCD calculations. For such calculations, Schutzmeier developed a fully automated program that will eventually be publicly released and will allow the computation of high multiplicity one-loop processes based on Feynman-diagram techniques. This code, and the methods newly developed to obtain it, have been instrumental to the completion of this project and will remain a powerful tool for future calculations. Indeed, the code has performed with very high efficiency on all processes tested so far, including various $2 \to 3$ processes and the very challenging $W + 3$ jet NLO calculation.

Since the results obtained by Reina's group are of great phenomenological relevance, a large portion of her research effort on this topic during the recent grant period has been devoted to studies requested by the experimental collaborations (ATLAS, CMS, CDF, and DØ). These studies do not always result in publications. In the following, we list just the most important studies, each of which has taken a considerable amount of time, but all of which have been acknowledged in experimental publications.

A very interesting study was conducted in collaboration with E. Thomson and C. Neu of CDF and has been reported in Ref. [CDF collaboration, arXiv 0909.1505] as well as Ref. [81]. Based on Ref. [78], Reina, in collaboration with J. Campbell (FNAL) and F. Febres Cordero provided NLO QCD theoretical predictions for W production with at least one b-jet at the Tevatron, and compared the prediction with the corresponding measurement from CDF. The results are found to be consistent with existing theoretical predictions based on `Pythia` and `Alpgen`, and confirm the substantial discrepancy between theoretical predictions and the experimental measurement. This puzzling anomaly is, of course, of great experimental relevance, since, as noted above, $W + b$ is a large background to the Higgs boson studies. Measurements from other

experiments will be necessary to resolve the issue.

Following new ideas that emerged during the 2009 Les Houches workshop, Reina, Febres-Cordero, and Wackeroth, in collaboration with J. Butterworth and G. Piacquadio from the ATLAS collaboration, presented in Ref. [82] a study of the $Wb\bar{b}$ background to WH searches at the LHC, focused on the boosted Higgs boson regime, where the structure of the heavy quark jets seems to enhance the signal to background ratio. New developments of this study are currently being examined following the new release of the implementation of the NLO calculation of $Wb\bar{b}$ production [77] into a full fledged NLO Monte Carlo program [79]. Reina and Febres Cordero provided the CMS Higgs Working Group (contact persons for these studies, Mariotti and Nikitenko) with two detailed studies of inclusive/exclusive production of $Z + b$-jets, which the experimental groups are using to interpret the collected data.

Hard Photon Production and Weak Boson Production with Top Quarks ($\gamma t\bar{t}, Zt\bar{t}$) (Reina, Hartanto, and Schutzmeier) Reina and Hartanto, in collaboration with T. Schutzmeier obtained results for $t\bar{t}\gamma$ hadroproduction including NLO QCD corrections. Two completely independent calculations have been developed, one of which formed the main part of Hartanto's doctoral project. The comparison between the two independent calculations was one of the first checks of the new automated package for one-loop QCD calculations developed by Schutzmeier.

Associated Scalar Production with Heavy Quark Pairs ($Ht\bar{t}$, $Hb\bar{b}$, $H + 1b$) (Reina) The associated production of a Higgs boson with heavy quarks ($Ht\bar{t}$, $H+1b$ jet, $H+2b$ jets) plays a very important role in searches for non-standard model Higgs bosons as well as in studies of the Higgs boson at both the Tevatron and the LHC.

In January 2010, Reina became a theory convener of the $Ht\bar{t}$ sub-group of the *LHC Higgs cross section working group*. The working group comprises the main contributors to the theoretical studies of Higgs boson production cross sections and the experimental contact persons for each production mode at both ATLAS and CMS. The goal is to formalize contact between the two communities and provide a common environment in which to coherently develop all Higgs boson analyses and studies during the first run of the LHC and beyond. The result of the first year of work appeared in January 2011 in the form of a CERN Yellow Report [83], containing a comprehensive review of all Higgs boson production modes, including the most up-to-date theoretical predictions for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 14$ TeV as well as a thorough and coherent analysis of all the main theoretical systematic uncertainties.

During 2011 the *LHC Higgs cross section working group* focused on exclusive predictions, which combine all Higgs boson production modes with the relevant decay modes for a low-mass or a high-mass Higgs boson. In this context, Reina worked on $t\bar{t}H$ production, with the idea of implementing the H and $t/\bar{t}$ decays in the narrow width approximation (for light Higgs bosons) and including the first order QCD corrections consistently.

In collaboration with S. Dawson (BNL) and D. Wackeroth, Reina is studying how to properly include b-quark mass effects in the calculation of $bg \to bH$ at higher order in QCD. Traditionally, this process has been calculated in the massless bottom quark approximation, but recent developments in the calculation of massive quark PDFs allows a more careful approach where bottom quark mass effects may be taken into account and have proven to be fairly important.

Associated Pseudoscalar Production with Heavy Quark Pairs ($At\bar{t}/Ab\bar{b}$) (Reina and Thayer) Reina and Thayer, in collaboration with C. Jackson calculated the hadronic production of a pseudoscalar in association with heavy quark pairs ($At\bar{t}$ and $Ab\bar{b}$), at NLO in QCD, using both traditional (Feynman diagram based) and new (on-shell recursion relations plus generalized unitarity cuts based) approaches. The traditional approach to this calculation is a generalization of the existing NLO QCD calculation of $Ht\bar{t}/Hb\bar{b}$ production (with the extra difficulty introduced by the pseudoscalar coupling proportional to γ_5) and can therefore be considered well tested ground. On the other hand, the application of on-shell recursion relations and generalized unitarity cuts to a fully massive NLO QCD calculation of a $2 \to 3$ process is newly tested if not untested ground (in the pseudoscalar case) and we can explore it by comparing partial and full results with the traditional approach.

Furthermore, this study, far from being purely academic, is of direct interest to those searching for new physics. Pseudoscalar Higgs bosons are predicted in any Two Higgs Doublet Model (such as the Higgs sector of the MSSM) and preferentially couple to either b or t quarks in different regions of the parameter space of the model. For massless quarks, the pseudoscalar and scalar production cross-sections are the same, whereas for massive quarks (of mass m_Q) they differ by effects of $O(m_Q^2/Q^2)$, where Q is a typical scale for the production process ($Q \simeq M_{H,A}$). Therefore, effects will be large for $At\bar{t}$. Moreover, pseudoscalar and scalar differential cross-sections differ both for massless and massive quarks and effects will be relevant for both $Ab\bar{b}$ and $At\bar{t}$ production.

Algebraic Techniques in Higher Order Loop Calculations (Reina and Rottmann) Reina and Rottmann completed a very general study of the applicability of algebraic techniques to the calculation of multi-loop integrals, focusing in particular on the systematic application to one-loop building blocks of multi-loop calculations, both massless and massive particles. In recent years, theorists have proposed very interesting applications of the algebraic structure of multiple polylogarithms and their generalizations to the calculation of NLO and NNLO QCD corrections for relevant massless processes in collider physics. NNLO QCD predictions are becoming the state of the art for theoretical predictions for several milestone processes at both e^+e^- and hadron colliders (think of $e^+e^- \to 3jets$, or $t\bar{t}$ production). Algebraic techniques have the potential of allowing a more systematic approach to extensive calculations

and Reina and her group have investigated their applicability to the case of two-loop QCD calculations for both massless and massive processes.

This has resulted in a very comprehensive classification of the strengths and limitations of all existing techniques. Moreover, definite progress has been made toward the construction of a general algorithm that will allow the calculation of a very broad family of integrals appearing in one- and two-loop calculations via an algebraic approach. Results have already been applied to reproduce two-loop massive calculations such as the calculation of heavy-quark effects in deep-inelastic-scattering form factors. These results were published in Ref. [84] and are the main core of Rottman's Ph.D. dissertation, which was completed in Spring 2011.

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