FINAL REPORT

DOE Award: DE FG02-97ER41029

University of Florida

1. DOE award number and name of institution (recipient)

Award number: DE-FG02-97ER41029
Institution: University of Florida

2. Project Title and name and contact info of lead PI

Project Title and Name: Neutrino Cross Sections II: Neutrino Boogaloo.
UF Task P3, Accelerator-Based Experimental Neutrino Physics

Lead (Only) PI Info:

Heather Ray
Department of Physics
P.O. Box 118440
Gainesville, FL 32611

(352) 392 9717 (office)

3. Date of report and period covered by the report

The University of Florida had their three-year review in the fall of 2009. Our three-year budget period ran from 2010 - 2013. Due to changes in our grant starting and ending dates, this report covers the period from November 2009 – June 2013.

4. Accomplishments supported by this award

4.1 Accomplishments in the November 2009 to March 2011 year

Heather Ray, P.I.
1) Veto wall validation code
2) Awarded URA travel money to stay at FNAL, summer 2010
3) Named a 2010 Kavli Fellow, 2010 US Kavli Frontiers of Science Symposium, U.S. National Academy of Sciences
4) Invited speaker for Kruger2010

Bari Osmanov, MINERvA Postdoc
Hardware:
1) Veto wall: assembly underground, cabling, general maintenance.
2) Expert in FEB replacement group. Occasional FEB replacements when needed. Preparation of supporting documentation.
3) Support person in PMT replacement group. Occasional PMT replacements when needed. Preparation of supporting documentation.
4) Pseudo-expert on power distribution group. In charge of AC Distribution Box, DC Bulk Supply, Fuse Chassis, FESB, UPS. Preparation of supporting documentation.

Software:
1) Supervision of simulation activities. GENIE-Geant4-Electronics simulation chain. Code additions to all three parts on the chain. Bug fixes.
2) Tuning of pe-energy conversion factor in optical model part of the simulation.
3) Improvements to the vertexing code in reconstruction.
4) Starting to work on optical cross-talk tuning and simulation of timing and afterpulsing

Joel Mousseau, MINERvA graduate student
Joel spent a good portion of this year working on hardware responsibilities for MINERvA, most notably the veto system and continuing expert status on the light injection calibration system. He advanced to candidacy in December, and has been working on hardware and had a toe in his thesis analysis since that time.

1) Veto wall: validated electronics and hardware, measured PMT afterpulsing and tuned discriminator thresholds in beam, finished reconstruction code, wrote event display for veto system
2) passed qualifying exam
3) presented a poster on MINERvA calibrations at Neutrino 2010
4) MINERvA invited talk at Miami2010
5) hadron reconstruction code
6) started work on DIS for thesis; presenting invited talk at DIS 2011 in April

Joe Grange, MiniBooNE graduate student
Joe has been awarded an APS grant to participate in a program that bolsters US-India scientific relations. In March he attended NuInt 2011 in India to present his first conference talk, on the first comparison of absolutely normalized Monte Carlo to antineutrino data of CCQE events in MiniBooNE with a focus on his wrong-sign measurement.

1) Veto wall simulation work for MINERvA
2) Poster presented at Neutrino 2010 on his work
3) Summer school talk for visiting undergraduates, 2010
4) Fully completed the wrong-sign analysis for MiniBooNE, paper submitted for publication
5) Awarded the APS IUSSTF travel grant to visit an institution in India and to present two lectures on MiniBooNE and nuclear modeling of CCQE events
6) Traveled to NuInt 2011 to present his first conference talk (25 minute talk) on his work

4.2 Accomplishments in the March 2011 to March 2012 year

Heather Ray, P.I.
1) Veto wall validation code
2) Invited speaker for Heidelberg's Graduate Days. Presented 15(!) 45-minute lectures encompassing all things related to neutrinos
3) Presented a MINERvA talk at Villa Olmo ICATPP conference
4) Invited speaker for Aspen 2012: The Hunt for New Physics, presented an overview of the latest neutrino results

Bari Osmanov, MINERvA Postdoc
Hardware
1) Veto wall: installation and maintenance, including cabling, light-leak checks, HV tuning, and PMT replacement
2) Expert in FEB replacement group. Occasional FEB replacements when needed. Preparation of supporting documentation.
3) Support person in PMT replacement group. Occasional PMT replacements when needed. Preparation of supporting documentation.
4) Pseudo-expert on power distribution group. In charge of AC Distribution Box, DC Bulk Supply, Fuse Chassis, FESB, UPS. Preparation of supporting documentation.

Software
1) Support of full simulation chain of MINERvA experiment (code improvements, debugging)
    a. Neutrino interaction generation with GENIE and NuMI flux files as an input.
    b. Propagation of final state particles through detector (response) with Geant4.
    c. Simulation of electronics response (light creation and propagation in scintillator, attenuation (clear and WLS fiber), conversion to photo-electrons,

PMT response, FEB response (discriminators, ADCs), cross-talk simulation (optical, dynode and FEB), timing signal with dead-time correction, photo-electron-to-energy conversion.

2) Analysis of hadron showers in MINERvA detector
   a. Reconstruction techniques to isolate hadronic showers in the detector.
   b. Determination of vertex, direction and energy of the shower.
   c. Isolation of electromagnetic component of the hadron shower

Presentations

1) SBNW-2011 – Short Baseline Neutrino Workshop, Fermilab. Talk: MINERvA: present and future
2) DPF-2011 – Meeting of the Division of Particles and Fields of the American Physical Society, Rhode Island. Talk: MINERvA detector: description and performance (proceedings in arXiv:1109.2855)

Joel Mousseau, MINERvA graduate student

Joel spent a good portion of this year working on hardware responsibilities for MINERvA, most notably the veto system, and on contributing to the global analysis toolkit effort. He has completely taken charge and responsibility for the entire veto wall system.

Physics

1) Lead installation of veto wall
2) Lead commissioning of veto wall
3) Supervised and mentored UF undergraduate located at FNAL during the summer
4) Designed and implemented live-time monitoring tools for the Veto Wall.
5) Wrote reconstruction software matching MINERvA muon tracks to Veto Wall hits
6) Wrote software simulating the MINERvA cryogenic target.
7) Wrote software extrapolating MINERvA muon tracks into the cryogenic target
8) Assisted in overhauling MINERvA's software framework

Presentations

1) Presented a talk at DIS2011 on his thesis topic
2) Proceedings from DIS2011
3) Gave graduate student overview talk at 2011 June FNAL User's Meeting
4) Presented a poster showing MINERvA's future DIS physics capability during the FNAL User's Meeting, Jun. 2011

Awards

1) Received student travel award from University of Florida to attend the 20th International Workshop on Deep-Inelastic Scattering and Related Subjects at Bonn, Germany (April 2012)

Other Activities

1) Attended Intensity Frontier one day workshop at Fermilab (Dec. 2011)

2) As a member of the Fermilab GSA, a graduate student organization that liasons with the laboratory, he
   a. Co-organized New Perspectives 2011 conference (he and Joe did lots of work for this, and it was incredibly successful)
   b. Assisted in moving the FNAL graduate student guide to life from a static html site to a community sponsored and maintained wiki
   c. Conducted surveys studying usage of fermilab on site taxi usage
   d. Assisted in organizing Gradute Student lunchtime talks (Winter / Spring 2011)

Joe Grange, MiniBooNE graduate student
Joe has continued to make good progress towards his thesis.

Physics
1) Published paper describing the wrong sign extraction in his data sample
2) Performed a CC dirt study using the veto data, producing the highest purity measurement of dirt ever at MB (got to ~80% dirt).
3) As senior student on MB, has done many checks and tasks for other analyses e.g. the CC dirt event study, a timing studies, and quick-turnaround data quality checks in his sample to have confidence in oscillation sample
4) Provided additional support for the MINERvA veto wall installation and commissioning.

Presentations
1) Presented two seminars at Aligarh Muslim U., India
2) Presented a plenary talk on nubar CCQE given at NuInt11. Only a handful of students had talks.
3) Presented the User's Meeting talk, a general MiniBooNE update.
4) Presented a talk at Miami 2011, a general MiniBooNE talk.
5) Gave a lecture on nuclear simulation to GSA lecture series at Fermilab

Awards
1) U Florida Department of Physics Charles F Hooper Memorial Award 2011, for outstanding graduate students
2) Student contribution award, Miami 2011
3) IUSSTF (Indo-US Science and Technology Forum, http://www.aps.org/programs/international/us-india-travel.cfm) travel grant
4) Won a position in the EDIT 2012 detector school; only ~25% of the applicants are accepted.

Other Activities
1) Helped Aligarh folks use and implement Nuance, a neutrino generator. Still regularly communicates with them. (see last year, he won an APS travel grant to visit an institution in India and to present 2 lectures on MiniBooNE and nuclear modeling of CCQE events)
2) As a member of the Fermilab GSA, a graduate student organization that liasons with the laboratory, he

a. co-organized New Perspectives 2011 conference (he and Joel did lots of work for this, and it was incredibly successful)
b. continued successful weekly seminar series by and for grad students at the lab
c. went to DC to lobby congress for science funding
d. ported the graduate student Guide to Life to an interactive wiki format

3) Four presentations to elementary through high school kids on physics at public schools + libraries.
4) Fermilab Ramsey Auditorium committee member (only student on it)

4.3 Accomplishments in the March 2012 to June 2013 year

Heather Ray, P.I.

1) Presented several talks and posters:
   a. ``MINERvA: Inclusive muon neutrino CC Cross Section Ratio'' (poster), ICHEP, Melbourne Australia. July 2012
   b. INVITED CONFERENCE TALK: ``Recent Cross Section Results from MiniBooNE'', ICHEP, Melbourne Australia. July 2012
   c. INVITED SEMINAR: "MINERvA: Cross Sections and Beyond!", Argonne National Laboratory HEP Division Seminar, November 28, 2012
   d. INVITED WORKSHOP TALK: "OscSNS", Coherent Scattering Workshop, Fermilab. October 2012
   e. INVITED CONFERENCE TALK: "OscSNS", Next Generation Nucleon Decay and Neutrino Detectors, Fermilab. October 2012
   f. INVITED WORKSHOP TALK: ``Deep Inelastic Scattering Now and in the PX Era'', Project X Physics Workshop, Fermilab. June 2012
   g. INVITED WORKSHOP TALK: ``Wee Baseline Experiments'', Project X Physics Workshop, Fermilab. June 2012
   h. INVITED CONFERENCE TALK: ``The hunt for new physics: Latest results from the neutrino sector'', The Hunt for New Physics, Aspen CO. February 2012
2) Session Organizer, NuINT 2012 International Neutrino Interactions Conference
3) Served on a review panel for the Department of Energy national laboratory high energy physics intensity frontier research program

Bari Osmanov, MINERvA Postdoc

Bari left the group in 2012, for a permanent position outside the country.

Joel Mousseau, MINERvA graduate student

Joel has finally been able to step away from the veto wall responsibilities, and has continued to make strong progress towards his thesis analysis.

Physics

1) Developed energy resolution code for the Nuclear Target analysis, allowing separa-

tion of detector and physics effects on the analysis
2) Explored an alternate recoil reconstruction algorithm, to better measure the hadronic energy shower from neutrino interactions in our detector
3) Debugged and improved the muon energy uncertainty calculation
4) Performed a study to determine the impact of the hadronic energy resolution on DIS events
5) Developed a study to quantify the impact of various levels of improvement in the energy resolution on the DIS analysis

Presentations
1) INVITED: Conference presentation on his thesis work, DIS 2012, Germany, March 2012. Published proceedings.

Awards
1) Won a UF Travel Award to attend the DIS 2012 conference, Bonn Germany. April 2012

Other Activities
1) On the editorial committee for MINERvA's NIM paper
2) Member of MINERvA's Speakers Committee

Joe Grange, MiniBooNE graduate student
During this funding year Joe has successfully defended, graduated, and accepted a job at Argonne National Laboratory.

Physics
1) Finalized the anti-neutrino QE cross-section measurement
2) Officially took over monitoring Michel distributions for MiniBooNE
3) Performed the QE analysis for few-week beam-off-target run, in preparation for a dark matter study
4) Performed a preliminary nu/nubar correlation study
5) Performed the first demonstration of mu+ polarization in MiniBooNE data
6) Performed the combined analysis of nubar NCE/CCQE results, including implementing cancellation of flux errors

Presentations
1) Wine and Cheese seminar at Fermilab
2) INVITED: Conference talk on his thesis work, NuINT 2012, Rio, October 2012
3) INVITED: Conference talk on his thesis work, NNN 2012, Fermilab, October 2012
4) Project X Physics Study, 2012
5) Neutrino physics seminar, University of Puget Sound
6) INVITED: physics seminar, SLAC
7) INVITED: physics seminar, Indiana University
8) INVITED: York University
9) INVITED: Argonne National Laboratory
10) INVITED: UIUC

11) INVITED: Cornell

Awards
1) UF Travel Award to attend NuINT 2012 conference, Rio Brazil. October 2012
2) Competitive slot at EDIT 2012 detector school; only ~25% of the applicants are accepted

5. List of papers

1. A.A. Aguilar-Arevalo et al., Measurement of the Neutrino Component of an Anti-Neutrino Beam Observed by a Non-Magnetized Detector, arXiv:1102.1964 [hep-ex], Phys. Rev. D84, 072005 (2011)
   Joe Grange is the primary author on this paper. This paper discusses how to extract the wrong-sign contamination present in a data sample, using a non-magnetized detector. This is a vital component of his thesis analysis and is of high interest to the experimental neutrino community.

2. K. N. Abazajian, M. A. Acero, S. K. Agarwalla, A. A. Aguilar-Arevalo, C. H. Albright, S. Antusch, C. A. Arguelles and A. B. Balantekin et al., "Light Sterile Neutrinos: A White Paper," arXiv:1204.5379 [hep-ph], 281 pp.

3. I. Stancu, Z. Djurcic, D. Smith, R. Ford, T. Kobilarcik, W. Marsh, C. D. Moore and J. Grange et al., "Letter of Intent to Build a MiniBooNE Near Detector: BooNE," FERMILAB-PROPOSAL-1002, 43 pp.

4. J. L. Hewett, et al, "Fundamental Physics at the Intensity Frontier", arXiv:1205.2671

5. A.A. Aguilar-Arevalo et al., "Low Mass WIMP Searches with a Neutrino Experiment: A Proposal for Further MiniBooNE Running", arXiv: 1211.2258, Proposal submitted to the FNAL PAC Oct 15 2012

6. A.A. Aguilar-Arevalo et al., "Letter of Intent: A new investigation of numu to nue oscillations with improved sensitivity in an enhanced MiniBooNE experiment", arXiv: 1210.2296, Letter of intent submitted to Fermilab for consideration, 10/12

7. A.A. Aguilar-Arevalo et al., "First Measurement of the Muon Anti-Neutrino Double-Differential Charged Current Quasi-Elastic Cross Section", arXiv: 1301.7067, Phys. Rev. D88, 032001 (2013)
   Joe Grange is the primary author on this paper. This is his thesis analysis.

We are just now submitting the first MINERvA physics papers.

6. List of people working on this research activity

The people supported by funds during this grant are:

Heather Ray, P.I., 2 months summer salary

Bari Osmanov, postdoc, 57% of salary covered by DOE (25K or 0.45 FTE from the supplemental, ~6.5K or 0.12 FTE from my base grant), rest by my startup funds, until his departure in September, 2012.

Joe Grange, graduate student on MiniBooNE, 100% covered by DOE one-shot until his graduation in April, 2013.

Joel Mousseau, graduate student on MINERvA, 100% covered by DOE

6.1 Faculty

Heather Ray, Assistant Professor during the time of this grant. I joined the Department in August 2007 having completed my PhD from University of Michigan in 2004 and post-doctoral research on MiniBooNE as a Director's Funded Fellow at Los Alamos National Laboratory. I founded the Experimental Neutrino Physics group at UF. My group joined MINERvA in November, 2008. My main efforts are focused on MINERvA, on the neutrino-Fe DIS physics analysis. I also continue to be involved with MiniBooNE; my graduate student is performing the world's first muon anti-neutrino CCQE cross section measurement in MiniBooNE's energy range. I am co-spokesperson for a proposal to perform neutrino measurements at the Oak Ridge Spallation Neutron Source using the OscSNS neutrino detector.

6.2 Research Associates

Bari Osmanov, Post-Doctoral Research Assistant, joined my group in January, 2008. He left the group in the fall of 2012 for a job in his home country. He was awarded a European Atomic Energy Community (EURATOM) fellowship for his work on transmutation of minor actinides in 2006. Bari was the main presence of UF at Fermilab. He was primarily focused on MINERvA.

6.3 Graduate Students

Joseph Grange graduated in the spring of 2013. He was the sole person working on the muon anti-neutrino CCQE analysis for MiniBooNE. He has published two journal articles relating to his thesis work.

Joel Mousseau is in his sixth year as a graduate student at UF. He has spent much of the first few years helping to build the MINERvA detector, and leading our hardware contribution to MINERvA, the veto wall. His thesis topic is the neutrino-Fe DIS physics analysis.

TASK P1/Task J

Experimental Research at the Energy Frontier in High Energy Physics

Final Report for period July 1, 2010 – June 30, 2013
PI: G. Mitselmakher
Co-PIs: D. Acosta, P. Avery, I.K. Furic, J. Konigsberg, A. Korytov, J. Yelton

1. Introduction

The University of Florida group is one of the largest US university groups in CMS, comprising around 40 scientists (PhDs, graduate students, engineers). We have made significant contributions over many years to all areas in CMS: physics analyses, detector, electronics, trigger, software, computing, operations, and management.

The main focus of the UF group in CMS during the grant period has been on the CMS data analysis, but in addition the group has made many contributions to CMS operations. During 2010-13, UF has had leading roles in several key CMS physics analyses spanning Higgs boson, SUSY and BSM physics searches as well as SM physics measurements.

2. Personnel

2.1 Faculty

Darin Acosta, Professor, is the Project Manager for the CMS Level-1 Trigger for the 2012-13 term and held the position of CMS deputy Physics Coordinator for 2010-11, and as such was responsible for helping coordinate the CMS physics program and the final internal review of results. Physics analysis activities during the grant period included Higgs searches (b-bbar and dimuon decay channels), the differential cross section of the Drell-Yan p_T spectrum, and the search for heavy particle decays to Z. He also co-managed the L1 CSC Muon trigger project with Prof. Furic.

Paul Avery, Professor, was Director of two national Grid initiatives, co-PI of several other national computing initiatives and helped establish the LHC Grid computing model in the U.S. During the grant period, he directed the Florida CMS Tier-2 center, and was actively involved in the UF group's effort on Higgs searches. Avery also directed *Thomas Jordan*, who is Project Manager for QuarkNet

Ivan Furic, Associate Professor, joined the Department in August 2007. His physics research interests are searches for new physics in final states involving muons and H → b bbar searches. Furic was coordinator of the Exotica Resonances subgroup 2010-2012. In 2008, he received the DOE award for a proposal dedicated to $Z'\to\mu\mu$ searches at CMS. In that same year, Dr. Furic was awarded a Sloan Research Fellowship in Physics. Funding from these sources ended with the award of tenure (August 2012), and the related activities merged into this grant. Furic co-manages the L1 CSC

Muon Trigger project with Prof. Acosta.

Jacobo Konigsberg, Research Professor, was the UF CDF group coordinator since 1996 and was co-spokesperson of CDF for two terms, 2006-2010. He has transitioned to CMS and was an LPC fellow (for 2011-2012). During the funding period he was appointed as convener of the CMS Higgs →bb Group, played a leading role in the CMS VH; H→ bb analysis, coordinated the UF group in this effort, and has been a member of the CMS Publications Board.

Andrey Korytov, Professor, was the CMS Higgs Group convener in 2009-2010 and the CMS Higgs Combination and Properties Group convener in 2011-2012. He was leading the effort on combining searches in multiple Higgs boson channels that culminated in the discovery of the Higgs boson candidate in Summer of 2012. He played a key role in the observation of the Standard Model Higgs boson in the golden decay channel $H \to ZZ \to 4l$ and measurements of its properties (mass, spin-parity). He is also an important member of the UF SUSY group, and made a number of critical contributions that helped define the UF group's role in the SUSY searches in CMS.

Guenakh Mitselmakher, Distinguished Professor. From was an elected Co-Chair of the CMS Muon Project Institutional Board (2008-12). During the grant period, he worked on the Higgs searches in the $Higgs \to ZZ \to 4l$ channel, and on searches of SUSY with two same sign muons in the final state. He also contributed to the M&O of the CMS CSC project and leads the CSC High Voltage system project. He was on sabbatical for 2011-2012 as a Guest Professor at the University of Zurich, based at CERN.

John Yelton, Professor, worked on the CLEO experiment which stopped taking data before the grant period, but continues to publish papers. His analysis thrust on CMS is the search for SUSY signals, and he worked closely with post-docs Didar Dobur and Lesya Shchutska, and also supervised graduate student Lana Muniz whose thesis will be on SUSY searches with same-sign di-leptons + jets +MET His four-year term as Chairman of the Physics Department ended summer 2013.

2.2 Research Associates

Still Employed 6/30/2013:

Didar Dobur began working for our group Nov. 2008 and is based at CERN. She worked on same-sign SUSY searches, and was the Co-Convener of the Leptonic SUSY group. She was an organizer of the Bodrum CMS physics week in Bodrum, Turkey. She has led the same-sign SUSY search and multi-lepton SUSY search.

Gian Piero Di Giovanni joined our group in September 2008 (Ph.D. from Universite de Paris 6) and has been based at CERN. He led the measurement of the distribution of the transverse momentum of Z bosons at CMS in the dimuon decay channel for $\sqrt{s}=7$ TeV and is currently repeating it for $\sqrt{s}=8$ TeV. He also led a derived search for new heavy particles decaying to boosted Z's, and we have adapted it to a search for $H \to \mu\mu$.

Alexey Drozdetskiy was hired in August 2007 (Ph.D. from UF) and was based at CERN. In 2011, he led the Higgs boson search in the H→ZZ→llνν channel, the most sensitive search for the high mass Higgs boson. He also led the analysis reporting the observation of the rare Z→4l decays at LHC, an important standard candle for H→ZZ→4l search. In 2012-2013, he led the H→ZZ→4l search, which was a main channel in the CMS Higgs observation paper. He takes up a Research Assistant Professor position at Notre Dame in September 2013.

Michele DeGruttola was hired in January 2011 (Ph.D. from University of Naples), is based at CERN and has worked on Zprime searches. He was an LPC fellow (2011-2012), plays a leading role in the CMS Higgs → bb analysis group, and has permormed the analysis of the ZH→νν,bb mode. He is currently pursuing a search for Higgs decays into invisible channels in the missing ET + b-jets final state and he was recently appointed convenor of the CMS JETMET Trigger group. He also worked on projections of Higgs coupling uncertainties for high-luminosity LHC scenarios for Snowmass 2013.

Mingshui Chen was hired in July 2009 (Ph.D. from IHEP, Beijing) and was based at CERN. He was the lead member of the CMS Higgs Combination and Properties Group responsible for developing the combination procedure, software, and one of the two people in CMS who actually carried out all CMS Higgs boson search combinations in 2011 and 2012. He gave the approval talk on the observation of the Higgs boson candidate inside the CMS Collaboration before the discovery was made public on July 4, 2012. He played an important role in the the Higgs boson search in the H→ZZ→4l channel and on the SUSY searches. He is employed starting August 2013 as a faculty member at IHEP, Beijing.

Anna Kropivnitskaya was hired in August 2009 (Ph.D. from ITEP, Moscow), partly using USCMS funds, and led our trigger operations at CERN for the Level-1 CSC Track-Finder. This includes maintenance and operations and the development of novel new algorithms for reducing the trigger rate while keeping the muon trigger efficiency high. She then joined the effort on measuring of the distribution of Z p_T at $\sqrt{s} = 8$ TeV, the search for boosted Z's, and a search for H→ μμ.

Lesya Shchutska was hired in August 2012 (PhD from École Polytechnique Fédérale de Lausanne) to replace Ronald Remington and has continued our group's effort on SUSY search in same-sign di-lepton and tri-lepton modes.

Souvik Das was hired in July 2011 (Ph.D. from Cornell), and has been based at the LPC, Fermilab. He will be an LPC Fellow during 2013. He has worked on the Higgs →bb search and made very significant contributions to the development and implementation of new triggers to enhance CMS's sensitivity to the ZH→νν,bb channel. He is performing a new search for resonant di-Higgs production in the HH→bb,bb and has started a new project in the simulation of tracking triggers for the CMS phase 2 upgrade.

Predag Milenovic, was hired in October 2011 (Ph.D. from ETH), and was based at CERN. His research is focused on the H→ZZ→4l search. Milenovic made a number of critical contributions to the CMS H→ZZ→4l results, in particular related to developing the method of evaluating the reducible four-lepton backgrounds and measurements of the spin-parity properties of the observed Higgs boson candidate.

Other post-doc who worked on the project 2010-2013:

Nathan Goldschmidt worked at CDF on searches for new resonances in top-antitop pro duction. He also worked on the CLC detector operations and on the CDF luminosity measurements. At the end of 2011, he took a position as Applied Physicist at SLAC with the LCLS group.

Valdas Rapsevicius worked on the EMU Data Quality Monitoring and was the EMU DQM contact person at CERN. He took a position with Fermilab to work on CMS DQM and databases in 2011.

Alexander Sukhanov worked on measurements of top-antitop production cross section, top quark mass, and anomalous production mechanisms in the "all-jets" final state. He was co-leader of the all-jets top subgroup. Sukhanov served as co-leader of the CDF luminosity detector group and was co-leader of the CDF silicon detector group.

Jonatan Piedra was a postdoc working on CMS with a focus on the preparation for the measurement of the Z production cross section in the $Z \rightarrow \mu^+\mu^-$ final state and following up with searches for high-mass Z' decays. He was central to the analysis of CMS cosmic data being gathered with full magnetic field (CRAFT). Piedra is now a Research Fellow at the University of Cantabria, Spain.

Ronald Remington obtained his thesis on initial SUSY searches with the 2010 data, and then was continued as a post-doc to became the leader in the extension of the effort in the search for electro-weak production of SUSY. In 2011 he took a staff scientist position with the Applied Physics Laboratory (affiliated with Johns Hopkins University)

Dayong Wang was a postdoc who worked first on trigger hardware and latterly on SUSY and MET algorithms. He left in 2011 to be a post-doc based at CERN and has now taken a junior faculty position in China.

2.3 Graduate Students

Continuing:

Matthew Fisher (Advisor: **Furic)** is working with Konigsberg and Furic on $H \rightarrow bb$ searches. Fisher is the lead CMS analyzer for the $ZH \rightarrow \mu\mu,bb$ final state. Fisher is stationed at CERN and is an active pager carrier for the CSC L1 trigger system, for which he also supports the run-control (“online”) software package.

Nikoloz Skhirtladze (Advisors: **Korytov, Mitselmakher)** works on the SUSY search with same-sign dileptons and tri-leptons. He develops and supports a number of CMS triggers related to these searches. Nikoloz is based at CERN.

Tonguang Cheng (Advisors: **Mitselmakher, Korytov)** works on the $H \rightarrow ZZ \rightarrow 4l$ search and observation of $Z \rightarrow 4l$. Cheng has made critical contributions to the observation of the Higgs boson candidate in the H→ZZ→4l channel and to measurements of the Higgs boson candidate properties; in particular, to its mass measurement. He is based at CERN

Lana Muniz (Advisor: **Yelton)** has taken over from Remington some of his responsibilities in the SUSY same-sign di-leptons program, including making the data skims for analysis by the entire UF SUSY group. She is also working on reducing and more accurately measuring the background to same-sign SUSY signals and plans to write her thesis on the analysis of the 2012 data. She is based at UF.

Justin Hugon (Advisor: **Acosta)** has contributed to improvements to the sensitivity for the Higgs to b bbar search for the 2012 analysis, after having adapted our Z P_T differential cross section measurement based on 2010 data to the Rivet framework for comparison to other experiments and theoretical calculations. He is currently conducting a search for the Standard Model decay H→ μμ for his dissertation. He supports our CSC trigger operations and trigger upgrade studies. He relocated to CERN in 2012.

Matt Snowball (Advisors: **Avery, Korytov)** works on the H→ZZ→4l search and observation of Z→4l. Snowball has made critical contributions to the observation of the Higgs boson candidate in the H→ZZ→4l channel and has been the lead person in exploiting the Z→4l decays (first observed by the UF group) as a "standard candle" in measurements of the Higgs boson candidate properties. He is based at UF but spends part of his summers at CERN.

Aurelijus Rinkevicius (Advisor: **Mitselmakher, Korytov)** works on the H→ZZ→4l search and observation of Z→4l. Rinkevicius has made critical contributions to the observation of the Higgs boson candidate in the H→ZZ→4l channel and to establishing its spin-parity quantum numbers. He relocated to CERN starting May 2012.

Jia Fu Low (Advisor: **Konigsberg)** is a fourth-year student, based at the LPC at Fermilab, working on Higgs physics. He performed trigger studies for the ZH→νν,bb channel and analyzed the full CMS run 1 data in this channel. He is currently pursuing a search for Higgs decays into invisible channels in the missing ET + b-jets final state and is working on JETMET trigger studies for Run 2.

David Curry (Advisors: **Acosta, Furic**) is a third-year student who started working in our group during summer 2012 on the Higgs searches and the search for boosted Z's, supported as an Institute of High Energy Physics and Astrophysics (IHEPA) Fellow.

Matt Carver (Advisor: **Acosta**) is a third-year student who started working in our group during summer 2012 on Level-1 trigger upgrade studies, supported by an IHEPA Fellowship.

Students Supported by the Grant who Graduated 2010-2013:

Nick Kypreos (CMS, Advisor**: Furic**) "Search for Heavy Narrow Resonances Decaying to Dimuons with the CMS Detector" May 2013. Now employed by Amazon Web Services, Seattle, WA.

Joseph Gartner (CMS, Advisor: **Acosta)** "The Study of the Z Boson Transverse Momentum Spectrum Recorded by the Compact Muon Solenoid From 2010 Large Hadron Collider Data". Dec. 2011. He is now a software developer with SumTotal, Gainesville.

Ronald Remington (CMS, Advisors: **Yelton,** *Matchev***)** "Searching for Supersymmetry with Same-sign Di-Leptons Using the CMS Experiment at the Large Hadron Collider", August 2011. He was then employed by us as post-doc before moving to a scientific research position as detailed above.

Michael Schmitt (CMS, Advisor: Avery) "Measurement of the Charge Ratio of Atmospheric Muons at the Compact Muon Solenoid in Events with Momenta Between 5 GeV/c and 1 TeV/c", August 2010. He is now a scientist working for L-3 Communications, Boston, working on X-ray sensing.

Yuriy Pakhotin (CMS, Advisors: Mitselmakher, Korytov) "Compact Muon Solenoid Experiment Discovery Potential for Supersymmetry in Same-Charge Di-lepton Events," August 2010. He is now a postdoc with TAMU, working on CMS.

3. CMS: Summary of Work 2010-2013

In this section we describe our recent contributions related to CMS operation and CMS physics program.

3.1 CMS Service Tasks and Upgrade

Cathode Strip Chambers

Participants: **Korytov, Mitselmakher, Cheng, Curry, Kypreos, Milenovic, Skhirtladze, Snowball,** *Barashko*

The Endcap Muon System (EMU) and its Cathode Strip Chambers (CSCs) are of special significance for our group. **Mitselmakher** was the EMU construction project manager ($40M); **Korytov** led the design and construction of CSCs ($18M). The system has 468 large CSCs, arranged in four stations on each side of CMS. The total number of readout channels in the system is about 500K, and the total number of wires is ~2M.

Korytov was a part of the US CMS Endcap Muon System L3 management structure, where he served as special technical advisor. **Skhirtladze** and **Kypreos** have been among a few CSC Expert Operators (CEOs). We are actively involved in CSC-specific shifts, for which the UF group developed a dedicated standalone DQM system (**Korytov**, Milenovic, Cheng.)

CSC High Voltage System

Participants: **Mitselmakher, Korytov, Milenovic, Rinkevicius,** *Barashko, Madorsky*

The UF group designed and produced the high voltage system for the cathode strip chambers. The system has about 9,000 individually controlled channels capable of providing up to 4 kV with a better than 5-ppm stability. During the last three years of operation, the UF group has provided continuous monitoring of the system performance, diagnostic of problems, and repairs, as needed.

CSC Data Quality Monitoring

Participants: **Korytov,** *Barashko***, Cheng, Milenovic**

The UF groups developed and maintains the Data Quality Monitoring for the cathode strip chambers. This involves monitoring performance of about 500K channels: analog cathode strip signals, digital anode wire signals, both strip and wire trigger primitives.

CSC Performance and local segment reconstruction

Participants: **Korytov, Mitselmakher, Cheng, Drozdetskiy, Milenovic, Shchutska**

In 2013, the UF groups launched the effort on systematic studies of the CSC performance over the LHC Run I, initially focusing on evaluation of whether there were signs of the detector performance deterioration with the integrated luminosity—these studies have become critical in the context of the current assumptions that CSCs will continue to be operational up to 3000 fb^{-1}, way above the initial specs for the system. We also prepare a better optimized reconstruction of track segments in CSC in preparations for the high luminosity operation.

L1 Trigger Project Management

Participants: **Acosta**

Acosta was appointed as the project manager for the Level-1 Trigger of CMS for 2012-13. The CMS Level-1 Trigger is comprised of a large collection of custom digital electronics that forms the first pass (of two) at filtering the huge LHC collision rate down to manageable level for further processing (40 MHz to 100 kHz). Acosta was responsible for managing the project to during the 2012-13 LHC run (hardware and software), and for preparing the upgrade of the trigger system during the subsequent LHC shutdowns in 2013 and 2018. The project prepared a Technical Design Report on the trigger upgrade for release in 2013. As the project manager, Acosta participated in the Extended Executive Board and Management Board meetings of CMS.

CSC L1 Trigger

Participants: **Acosta, Furic, Di Giovanni, Kropinitskaya, Fisher, Hugon**, *Madorsky, Scurlock*

Since the start of the current LHC run (and even before during commissioning), the UF group has had to maintain and operate the CSC Track-Finder for the Level-1 Trigger system of CMS. In 2012 we achieved a factor of two reduction in the total single muon trigger rate with very little induced inefficiency from that achieved in 2011. We are able to maintain an efficient muon trigger with wide acceptance able to meet the energy frontier needs of Higgs and BSM searches, and yet also able to feed a B-physics program with a very low momentum dimuon trigger

CSC L1 Trigger upgrades

Participants: **Acosta, Furic, Di Giovanni, Kropinitskaya, Carver, Curry,** *Madorsky, Scurlock* In the past several years we have performed R&D on an upgrade to the CSC Track-Finder Trigger system to handle the increased luminosity, occupancy and performance requirements for a Level-1 muon trigger operating at the Phase 1 Upgrade of the LHC (i.e. luminosities reaching 2−4E34 and pile-up of 50−100 at a center-of-mass energy of 14 TeV). This requires pattern recognition algorithms able to accommodate much higher occupancy and further improvements to the momentum assignment algorithm in order to achieve a further rate reduction by a factor ~5.

Grid computing, UF CMS Tier 2

Participants: **Avery, Snowball,** *Kim, Fu, Bourilkov*

Avery directed the UF Tier-2 center throughout the grant period. This center actively supports computing, software and datasets for CMS physicists. Major issues involve support of CMS physics analysis and MC production, providing software support and installation for US CMS groups. The Tier-2 center equipment and staff (except Avery) are supported by NSF funds. He also is a founding member (co-PI) and former Council Chair of Open Science Grid, (www.opensciencegrid.org) the umbrella organization supporting LHC computing in the US. Almost all LHC computing is managed under OSG.

JETMET Triggers for Run 2

Participants: **Low, DeGruttola, Konigsberg**

During 2015 the LHC will run at ~13 TeV with bunches spaced by 25 ns and at high instantaneous luminosity, for which the event pileup is expected to be in the 30-50 range. In order for the physics program to not be affected, it is paramount for CMS to be able to operate MET+jet triggers at low enough thresholds and rates under these conditions. Our group is performing trigger studies, using 2012 data, to understand how to mitigate these effects and implement efficient, low-rate, triggers successfully.

3.2 LHC Physics

Introduction

The UF group has had considerable success in exploiting the rich physics program that the LHC data has opened up during the last three years. Our physics research program comprises Higgs, SUSY, and BSM searches; and SM physics measurements.

Up until the end of 2012, the LHC to delivered a total integrated luminosity of proton-proton collisions of approximately 25 fb^{-1}. Our on-going analysis program is dedicated to fully exploit the dataset gathered up until that shutdown. This includes improvements to and completion of the analyses that we have been working on all along during the last couple of years as well as extensions to these that explore new ideas, and preparations to develop a successful physics analysis program for 14 TeV running.

Physics and Technical Management

Acosta was CMS deputy physics coordinator for 2010-11, and thus responsible for coordinating the physics output of CMS across 15 physics analysis and object groups. This led to about 50 detector papers and nearly 100 physics papers for publication.

Avery is the director of the UF CMS Tier-2 center which provides computing support for CMS. He has directed, co-directed and participated in numerous national and regional computing and networking initiatives that support CMS cyberinfrastructure

Dobur acted as convener of the leptonic SUSY group, one of the most active groups in SUSY searches.

Drozdetskiy was the editor of the H→ZZ→4l papers, co-coordinated this discovery channel in CMS in 2012-2013.

Furic has served in 2010-12 as Coordinator of CMS Exotica Resonant Searches.

Konigsberg is convenor of the CMS Higgs→bb Group, has led the VH(bb) analysis, has been the editor of all CMS VH(bb) papers, co-edited the CMS Higgs papers, and is serving on the CMS Publications Committee.

Korytov was the CMS Higgs Group convener in 2009-2010 and the CMS Higgs Combination and Properties Group convener in 2011-2012. He was leading the effort on combining searches in multiple Higgs boson channels that culminated in the discovery of the Higgs boson candidate in Summer of 2012. He co-edited a number of the CMS Higgs papers.

Mitselmakher is a member of the CMS Muon Upgrade Strategy Group.

3.2.1 Higgs Physics

The discovery of a Higgs-like boson with a mass of about 125 GeV is the most exciting and important discovery in particle physics in the last several decades. The UF group has been at the forefront of the CMS effort and we have contributed very strongly to several key parts of this monumental enterprise.

Searches and study of the Higgs boson in the H→ZZ→4l channel

Participants: **Avery, Chen, Cheng, Drozdetskiy, Korytov,** *Matchev* **, Milenovic, Mitselmakher, Rinkevicijus, Snowball**

The H→ZZ→4l channel is critical for measuring Higgs boson's spin and CP-parity. The UF group made decisive contributions to the 2011 dataset analysis, published in Phys.

Rev. Lett. **108**, 111804 (2012). In 2012, **Drozdetskiy** was appointed to lead this search. The results of the H→ZZ→4l search (CMS PAS HIG-12-016, co-edited by Drozdetskiy) together with the H→γγ search results led to observation of a new boson with a mass near 125 GeV. The discovery was announced on July 4, 2012, and has been published in Phys. Letters B716 (2012) 30, followed by a more complete paper in JHEP 06 (2013) 081. In early 2013, using the H→ZZ→4l channel alone, CMS published the mass measurement of the Higgs boson candidate and unambiguously established that the new boson is not a pseudo-scalar (Phys. Rev. Lett. 110 (2013) 081803). The preliminary results obtained with the full Run I dataset were released in March of 2013 (CMS PAS HIG-13-002, co-edited by Drozdetskiy), where a number of alternative spin-one and spin-two hypotheses were tested and also excluded. In all these results, the UF group carried out the entire end-to-end analyses and made a number of distinct contributions, e.g.: developed models for signal and background four-lepton mass distributions, developed data-driven techniques for evaluating reducible backgrounds, developed tools for including matrix element information into the statistical analysis, introduced the method of using per-event four-lepton mass resolutions in the measurements of the Higgs boson mass, observed rare Z→4l decays now used as a "standard candle" for the studies of the Higgs boson properties, etc. The approval talk on the evidence for the new boson in the four-lepton final state was presented by **Drozdetskiy**. The approval talk on the spin-parity properties of the new boson in the four-lepton final state was presented by **Milenovic**. In collaboration with phenomenologists *Matchev* and *Gainer,* our group developed a public code MEKD (Phys. Rev. D97 (2013) 055006) for calculations of the leading-order matrix elements for X→ZZ→4l, where X can be either the SM Higgs boson or one of alternative exotic models from an ever-expanding list of options, and for qq→4l (background). The code has been used by CMS (Phys. Rev. Lett. 110 (2013) 081803; CMS PAS HIG-13-002).

Observation of Z→4l decays and first measurement of BR(Z→4l)

Participants: **Avery, Chen, Cheng, Drozdetskiy, Korytov,** *Matchev*, **Milenovic, Mitselmakher, Rinkevicius, Snowball**

The first observation of the rare Z→4l decays in pp collisions and the first measurement of the branching fraction BR(Z→4l) were carried out by the UF group in collaboration with the University of Wisconsin in 2012 (JHEP 12 (2012) 034). **Drozdetskiy** led this analysis and was the editor of the publication. The measured branching ratio BR(Z→4l) = $4.5 \pm 0.9 \times 10^{-6}$ agrees with the standard model predictions. The observation of Z→4l decays is an important prerequisite for discovering the Higgs boson and measurements of its properties in the H→ZZ→4l channel. The Z→4l peak has been already used by CMS for validation of the four-lepton mass scale in the context of the measuring the mass of the Higgs boson candidate.

Higgs in H→ZZ→2l2v channel

Participants: **Drozdetskiy, Rinkevicius, Snowball**

In 2010, the common perception in CMS was that the search for the standard model

Higgs boson in the $H \to ZZ \to 2l2\nu$ channel was not competitive. **Drozdetskiy** and Vartak from UCSD teamed up to give this channel another chance. By early 2011, they showed that the $H \to ZZ \to 2l2\nu$ could be improved and they turned it into the most sensitive channel for a Higgs boson of high mass. The results obtained with the 2011 data confirmed that the search in $H \to ZZ \to 2l2\nu$ is the most sensitive Higgs boson search above m_H=325 GeV. **Drozdetskiy** was co-editor of all CMS $H \to ZZ \to 2l2\nu$ results obtained with the 2011 data: EPS'11 (CMS PAS-HIG-11-005), LP'11 (CMS PAS-HIG-11-016), and a seminar at CERN (CMS PAS-HIG-11-026). The 2011 dataset results are published in JHEP 2012, No. 3, 40. The $H \to ZZ \to 2l2\nu$ channel led by our group, has been the major player in these results.

Search for Higgs boson in the H→bb channel

Participants: **Acosta, Das, De Gruttola, Fisher, Furic, Konigsberg, Low**

The observation of the H→bb decay is critical to help establish the true nature of the recently observed Higgs-like boson particle at 125 GeV. This relatively new UF effort, coordinated by **Konigsberg**, started in the Spring of 2011 and has been very fruitful. During 2011 the UF group, together with a group from Princeton, led the analysis in the very challenging WH(bb) and ZH(bb) modes. This work produced the first public H→bb result by CMS became a journal publication with the full 4.7 fb^{-1} 2011 dataset: Phys. Lett. B, 710 (2012). **Konigsberg** was the editor of all CMS VH→V,bb public analysis summary documents: CMS-PAS-HIG-11-012, CMS-PAS-HIG-11-031, CMS-PAS-HIG-12-019, and CMS-PAS-HIG-13-012. The latter describes the analysis that combines the complete 2011 7 TeV and the 2012 8 TeV datasets. Two of the five channels were analyzed end-to-end by the UF group: $ZH \to \nu\nu$,bb (**De Gruttola, Low, Konigsberg**) and $ZH \to \mu\mu$,bb (**Fisher, Furic**). The CMS VH→V,bb analysis has the best sensitivity compared to any other experiment, and the results provide the first indications of H→bb at the LHC at the 2-sigma level for a Higgs mass of 125 GeV. At each of the four rounds when CMS made the VH→V,bb results public, there have been internal pre-approval and approval presentations, **De Gruttola** was one of the presenters each time.

This work by our group is part of the following CMS publications: Phys. Lett. B710 (2012), **Phys. Lett. B716 (2012)** and **JHEP 06** (**2013**) **081. Konigsberg** edited fully the first one on VH(bb), and the H→bb sections on the last two, which are the CMS Higgs observation papers. He is currently editing the latest VH(bb) CMS publication with the full Run 1 dataset.

New analyses related to H→bb

Participants: Konigsberg, Furic, Das, Low, DeGruttola

As part of our program to test whether the newly discovered boson is a gateway to physics beyond the standard model, we perfomed a seach for possible invisible decays in the Z(bb)H(inv.) final state. Invisible Higgs decays do not play a role in the standard model and the observation of such will be clear evidence that this particle is not the standard model Higgs. The analysis is in its final stages and will become public in a couple of months. We are also performing a search for di-Higgs resonant production where a narrow resonance produces two 125 GeV Higgs particles, each decaying to bb. We have made good progress in this analysis and expect a public result by year's end. We have also turned around the VH(bb) analysis and searched for the standard model VZ(bb) production in the high-pt(V) regime. We measured the cross section for this process and a journal publication is under way.

Search for Higgs in the H→ μμ channel

Participants: **Acosta, Di Giovanni, Furic, Hugon, Kropivnitskaya**

We initiated a search for the rare Standard Model Higgs decay H→μμ by adapting our BSM searches for Z' and for highly boosted Z's and by leveraging our expertise in the other Higgs channels reported here. The overall goal is to concentrate on a narrow mass window around 125 GeV where the Higgs-like boson was recently discovered, and to use variables such as the dimuon P_T, dimuon angular information, and the presence of forward jets consistent with vector boson fusion production in order to discriminate the signal from other background processes. While the SM Higgs cross section times branching ratio is 10 times smaller than for H→γγ (but for which an excess was observed at 125 GeV already), the muon identification is very clean and the Drell-Yan background is well predicted. This channel is the only promising avenue to test the Higgs coupling to second generation fermions, and may also be sensitive to new physics contributions. Our strategy has evolved into dividing the analysis into many categories based on differing mass resolution and the number of final state jets. We expect a sensitivity at the level of 5 times the Standard Model expectation for the integrated luminosity recorded in 2011 and 2012, well below that recently reported by ATLAS. Postdoc **Kropivnitskaya** recently gave the preapproval talk to the Higgs group in June 2013, and we expect final approval and publication by the fall. This search will form the dissertation of **Hugon**. Postdoc **Di Giovanni** is also heavily involved, along with Profs. **Acosta** and **Furic** overseeing the analysis.

Higgs boson: combination of channels and properties measurements

Participants: **Korytov, Chen, Snowball, Curry, Cheng, Rinkevicius, Acosta, Avery, Konigsberg, Mitselmakher, Furic, Milenovic, DeGruttola, Das, Hugon and new students.**

Combination of many channels in one mega-analysis allows one to reach the maximum sensitivity in the Higgs boson search and is the only way to assess the nature of the now-observed new boson. Since 2011, **Korytov** is the CMS combination task leader and the CMS contact in the joint LHC Higgs combination group. They also carried out most of the CMS Higgs boson search combinations in 2011 and 2012. In 2011, Korytov represented CMS in the joint CMS+ATLAS effort on defining the Higgs combination procedure to be used by CMS and ATLAS (CMS NOTE-2011/005). **Korytov** was co-editor of all CMS combination results produced so far: EPS'11 (CMS PAS HIG-11-011), Lepton-Photon'11 (CMS PAS HIG-11-022), HCP'11 (CMS PAS HIG-11-023), December 13 CERN seminar (CMS PAS HIG-11-032), the 2011 dataset publication (Physics Letters B, 710 (2012) 26), Moriond'12 (CMS PAS HIG-12-008), and the ICHEP'12 results that brought in the discovery of a new boson with mass near 125 GeV (CMS PAS HIG-12-020). He also served as a co-editor of the long paper providing the detailed description of the five high-priority search analyses and their combination that resulted in the discovery (JHEP 06 (2013) 081).

CMS has observed a new boson with a mass near 125 GeV with 5σ significance. The first quantitative analysis of couplings of the observed state to vector bosons and fermions was reported by CMS at ICHEP (CMS PAS HIG-12-020). The approval talk on the discovery of the new boson and its compatibility with the SM Higgs boson was presented to the CMS Collaboration by **Chen**.

Korytov served as the co-editor of the long paper on the observation of the new boson; he was the responsible of the combination section.

Korytov was also a co-editor of the SM4 Higgs boson search paper (Phys. Lett. B 725 (2013) 36). This search now excludes the SM4 Higgs boson in the 110-600 GeV range and, hence, indirectly excludes a possibility of more than three fermionic generations.

3.2.2 SUSY Searches

For many years UF pioneered the techniques for SUSY searches in specific, low-background, channels. Although no signals have yet been found, each step up in LHC energy brings new possibilities for observable SUSY production. The UF group played a leading role in searches for SUSY using the 7 TeV data, and have continued these analyses through to completion of the 2012 running. At the same time the group has started in developing new search techniques targeting SUSY production at the high energy LHC running starting in 2015. We have focused on the following three searches: (1) same-sign dileptons, which provide an excellent probe for SUSY when gluinos, charginos, and LSP are kinematically accessible and charginos are lighter than gluinos; (2) tri-leptons which give the best access to an observation of SUSY when only gauginos can be produced at LHC; (3) multi-top production, which is the best suited signature in scenarios when gluinos, sTops, and LSP are the only SUSY particles that can be produced at LHC.

Searches for new physics involving same sign di-leptons+jets+MET

Participants: **Chen, Dobur, Korytov,** *Matchev*, **Mitselmakher, Muniz, Remington**, **Shchutska, Skhirtladze, Yelton**

For many years, UF led the preparations for SUSY searches in event topologies involving same-sign di-leptons, jets, and missing transverse energy. In 2010, the UF group suggested and used two distinct data driven methodologies for predicting QCD (**Remington**) and ttbar (**Dobur**) backgrounds. Together with Wurthwein from UCSD, **Korytov** was co-editor of the first CMS publication, and **Dobur** was one of three designated analysis co-ordinators (JHEP 06 (2011), 077). The group has remained as a co-leader of this analysis with the larger luminosity dataset: **Dobur** and **Remington** were co-editors of the summer 2011 update (CMS PAS SUS-11-010) and of the final 2011 dataset paper that was then published in Phys. Rev. Lett. 109, 071803 (August 16, 2012). Search results with 8 TeV data, now including at least two b-tagged jets, were released for the ICHEP conference (CMS PAS SUS-12-017) with the analysis approval talk presented to the CMS Collaboration by **Skhirtladze**. The analysis has now been published in JHEP 1303 (2013) 037.

Searches for new physics involving tri-leptons+jets+MET

Participants: **Chen, Dobur, Korytov,** *Matchev*, **Mitselmakher, Muniz, Remington**, **Shchutska, Skhirtladze, Yelton**

We have taken a leadership role in extending the SUSY searches to specific event topologies involving tri-leptons and missing energy. As the results from various SUSY searches using the 2011 data (including the same-sign dilepton analysis co-led by our group) produced ever-tighter limits on gluino/squark masses, the specific target of this search is the electroweak production of gauginos. The mass hierarchy assumes that sleptons are lighter than charginos, which would lead to a large yield of events with three and more leptons, and allows for carrying such a search already with the 2011 data. The final search signature we use is tri-leptons with large missing transverse energy. This analysis was published (JHEP 1211 (2012) 147) using the 7 TeV data. The search strategy and analysis was then re-optimized for the 8 TeV data and is available as a Public Analysis Summary (CMS PAS SUS-12-022). Under the leadership of **Shchutska**, the work has been extended to 3 leptons with addition of a b-tag (CMS PAS SUS-13-008) in an analysis designed to increase the sensitivity to SUSY models where multi-W/Z bosons are produced together with multi-b-quark jets and the lightest supersymmetric particle.

Searches for SUSY in Multi-Top Final States

Participants: **Chen, Dobur, Korytov,** *Matchev*, **Mitselmakher, Shchutska**, **Yelton**

We have started investigating the possibilities for a search for SUSY in tri-lepton and two same-sign di-leptons with b-jets, in the context of four-top final states. We have worked on investigation of the possible selection criteria, classification of the resulting experimental signatures, and evaluation of standard model backgrounds associated with each of them. The year 2013 has been devoted to carrying out the analysis with the full 2011+2012 dataset. **Dobur** and **Shchutska** have led the effort to bring this analysis to completion, with **Skhirtladze** presenting the approval talk to the collaboration. The expected date for submitting a journal paper, which will include limits on the same-sign top-pair production and four-top-quark production, is October 2013.

3.2.4 Beyond the Standard Model

Search for Highly Boosted Z's

Participants: **Acosta, Curry, DiGiovanni, Furic, Gartner, Hugon, Kropivnitskaya**, **Kypreos**

We have conducted a search for new heavy particles decaying via highly boosted Z bosons in the dimuon final state without constraints on the detectability and reconstruction of the other decay products. This novel UF-only analysis, proposed by **Acosta**, was led by **Di Giovanni** with the assistance of **Gartner**, **Kypreos** and **Kropivnitskaya**. We adapted the template fitting methodology of a Z' resonance search in the dilepton mass spectrum to a signal search in the $1/P_T$ distribution. The event selection of the Z P_T measurement reported earlier was modified to accommodate higher dimuon boosts (where the muon isolation criterion had to be modified to remain efficient) and was applied to the larger 5

fb^{-1} 2011 data sample. One intriguing boosted Z event has been found with P_T = 940 GeV, however. Limits are therefore derived on excited quark production and electroweak decay. **Di Giovanni** was the primary author of a paper, based on CMS PAS EXO-11-025, which has been published (Phys. Lett. B722 (2013) 28). This analysis rules out excited quark masses below 2.18 TeV in the limit of fully suppressed strong interactions.

Search for Z'→μμ

Participants: **Furic, Kypreos, De Gruttola**

The University of Florida group has been actively investigated in the search for heavy dimuon resonances since 2007. The Drell-Yan invariant mass spectrum is investigated for signatures of resonances decaying to dimuons. Resonances of high mass – O(1 TeV) decay into muons of high momenta.. Under the guidance of **Furic**, **Kypreos** has developed a novel technique to determine intrinsic biases of momentum measurement by the tracker system. The "cosmic endpoint" (the point in the spectrum for which $p_T \to \infty$) is displaced between the data and simulation if any high-momentum biases are present. Since cosmic muons are dominantly vertical, this expanded "generalized endpoint" allows us to study biases for all azimuthal flight directions, and to expand the study to include forward muons. **Kypreos** has also developed a fake-rate based method of estimating the QCD background level and shape for the search.

3.2.3 Standard Model

Z^0 Differential Cross Section Measurement $d\sigma/dp_T$

Participants: **Acosta, Furic, DiGiovanni,** *Bourilkov*, **Fisher, Gartner, Hugon, Kropivnitskaya, Kypreos**

The UF group was solely responsible for the measurement of the differential p_T cross section of Z bosons in the dimuon final state using the 2010 data sample at $\sqrt{s}$=7 TeV. **Di Giovanni** led the analysis effort with the first LHC data and was a co-editor of the publication that was written. The matrix inversion technique of unfolding the data was spearheaded **Gartner**, not only for the dimuon measurement but for the dielectron measurement as well. **Kropivnitskaya** performed the tag-and-probe efficiency measurements. The analysis was published in PRD in 2012, and also formed the core of Gartner's dissertation. **Hugon** implemented the published results into the "Rivet" framework, which allows anyone to compare the measured cross section with other experiments and with different Monte Carlo generators.

Drell-Yan Spectrum

Participants: **Furic,** *Bourilkov***, Kypreos**

The UF group has been a contributor to this analysis since its inception. **Kypreos** developed the software framework for unfolding the detector resolution, and provided one of the calculations of the QCD background. He was also in charge of determining the resolution-related systematic uncertainties.

Vector boson and J/ψ production

Participants: **Acosta, Chen, Drozdetskiy, Furic, Korytov, Kypreos, Mitselmakher**

As the first 7-TeV data started to trickle in in 2010, the UF group was strongly involved in the first measurements of vector boson and J/ψ production. For the first CMS paper on the Z/W cross section, we contributed the data-driven validation of the muon isolation efficiency using the technique of Lepton Kinematic Templates (LKT) developed by **Drozdetskiy**. The results are published in JHEP 2011, No 1, 1-40. For the first CMS paper on the J/ψ cross section, we contributed the data-driven technique for evaluation of uncorrelated di-muon backgrounds developed by **Chen**. This analysis is published in Eur. Phys. J. C71 (2011), 1575.

4. CDF: Summary of Past Work and Proposed Activity.

Detector and Operations: As part of the Run 2 upgrade, the CDF UF group was solely responsible for building and operating the CDF Luminosity Monitor: the "Cherenkov Luminosity Counters" (CLC). In addition, all luminosity measurements, online and offline, have been the sole responsibility of the UF group.

Physics: The Run 2 UF CDF research program comprises a diverse set of projects. In top quark physics we searched for resonant production of top pairs in the lepton+jets and the all-jets channels, and for top+jet resonances in the lepton+jets channel, we also measured the top quark mass in the all-jets channel. In searches for new physics we searched for first generation leptoquarks and for SUSY sTop and sBottom quarks in the missing-Et + jets channels. We also had a unique program of jet structure studies to test the limits of applicability of perturbative QCD in this realm. . Every physics research project has resulted in a journal publication and every student has graduated with a publication.

Leadership: The UF group has contributed in some of the most important leadership roles in the CDF experiment. These include Co-Spokesperson (**Konigsberg)**, Exotics and SUSY groups Co-Convener (**S.M. Wang**), SUSY group Co-Convener (**Nomerotski**), Top group Co-Convener (**Konigsberg**), Top All-jets group Co-Convener (**Sukhanov**), Top Monte Carlo coordinator (**Goldschmidt**), QCD group Co-Convener (*Field*), Luminosity Project Leader (**Konigsberg**)

5. Publications

5.1 Refereed Publications

CMS Here we only list those papers in which the UF group members made specific and major contributions to the analysis. October 2010 – September 2012.

Published:

1. CMS Collaboration, "Search for Anomalous Production of Highly Boosted Z Decays to Dimuons in pp Collisions at sqrt(s) = 7 TeV", Phys. Lett. B722 (2013) 28. (**Di Giovanni** – primary author and editor)
2. CMS Collaboration, "Search for standard-model-like Higgs boson with a mass in the range 145 to 1000 GeV at the LHC", Eur. Phys. J. C73 (2013) 2469
3. CMS Collaboration, "Measurement of the ZZ production cross section and search for anomalous coupling in 2l2l' final states in pp collisions at sqrt(s) = 7 TeV", JHEP 1301 (2013) 063.
4. CMS Collaboration, "Search for new physics in events with same-sign dileptons and b jets in pp collision at sqrt(s)=8 TeV." JHEP 1303 (2013) 037
5. CMS Collaboration, "Search for Anomolous Production of highly boosted Z bosons decaying to dimuons in pp collisions at sqrt(s) = 7 TeV", Phys. Lett. B722 (2013) 28
6. P. Avery et al., "Precision studies of the Higgs boson decay channel $H \rightarrow ZZ \rightarrow 4l$ with MEKD", Phys. Rev. D 97 (2013) 055006 (UF paper)
7. CMS Collaboration, "Searches for Higgs Bosons in pp Collisions at sqrt(s) =7 and 8 TeV in the Context of Four-Generation and Fermiophobic Models", Phys. Let. B725 (2013) 36 (**Korytov** -- editor)
8. CMS Collaboration, "Study of the Mass and Spin-Parity of the Higgs Boson Candidate Via Its Decays to Z Boson Pairs", Phys. Rev. Lett. 110 (2013) 081803.
9. CMS Collaboration, "Measurement of the tt production cross section in pp collisions at $\sqrt{s}$=7 TeV in dilepton final states containing a τ", (2012), arXiv:1203.6810 , Phys. Rev. D85 (2012), 112007 (**Korytov** -- review committee chair)
10. CMS Collaboration "Search for electroweak production of charginos and neutralinos using leptonic final states in pp collisions at sqrt(s) = 7 TeV", JHEP 1211 (2012) 147.
11. CMS Collaboration, "Search for new physics in events with same-sign dileptons and b-tagged jets in pp collisions at $\sqrt{s}$=7 TeV", arXiv:1205.3933, JHEP 1208 (2012) 110.
12. CMS Collaboration, "Observation of a new boson with mass near 125 GeV in pp collisions at sqrt(s) = 7 and 8 TeV", JHEP 06 (2013) 081 (**Konigsberg, Korytov** – co-editors)
13. CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at LHC", Phys. Lett. B716 (2012), 30-61. (**UF group** led two out of the five analyses described in the paper and the overall search combination)
14. CMS Collaboration, "Combined results of searches for a Higgs boson in pp collisions at sqrt(s)=7 TeV in the context of a standard model with four generations of fermions", Phys. Lett. B710 (2012) 26 (**Korytov** -- editor)
15. CMS Collaboration, "Measurement of the ZZ production cross section and search for anomalous coupling in 2l2l' final states in pp collisions at sqrt(s) = 7 TeV", JHEP 1301 (2013) 063.
16. CMS Collaboration, "Search for the electroweak production of charginos and neutralinos using leptonic final states in pp collisions at sqrt(s) = 7 TeV", JHEP 1211 (2012) 147.
17. CMS Collaboration, "Observation of Z decays to four leptons with the CMS detector at the LHC", JHEP 1212 (2012) 034 (**Drozdetskiy** -- editor)
18. CMS Collaboration, "Search for new physics with same-sign isolated dilepton events with jets and missing energy", (2012), arXiv:1205.6615 , Phys. Rev. Lett. 109, 071803 (August 16, 2012) (**Dobur, Remington** -- co-editors)
19. CMS Collaboration, "Search for a light charged Higgs boson in top quark decays in pp collisions at sqrt(s) = 7 TeV", (2012), JHEP 1207 (2012) 143 (**Korytov** -- review committee chair)
20. CMS Collaboration, "Search for the standard model Higgs boson in the $H \rightarrow ZZ \rightarrow 2l2\nu$ channel in pp collisions at $\sqrt{s}$ = 7 TeV", JHEP 2012, No. 3, 40 (**Drozdetskiy** -- co-editor, **Konigsberg** -- review committee chair)

21. CMS Collaboration, "Search for the standard model Higgs boson decaying to bottom quarks in pp collisions at sqrt(s)=7 TeV", Phys. Lett. B, 710 (2012) p.284. (**Konigsberg** -- editor).
22. CMS Collaboration, "Search for the standard model Higgs boson in the decay channel H→ ZZ→4l in pp collisions at $\sqrt{s}$ = 7 TeV", Phys. Rev. Lett. **108**, 111804 (2012)
23. CMS Collaboration, "Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s}$ = 7 TeV", Physics Letters B, 710 (2012), Pages 26-48 (**Korytov** -- co-editor)
24. CMS Collaboration, "Measurement of the Rapidity and Transverse Momentum Distributions of Z Bosons in pp Collisions at sqrt{s} = 7 TeV", Phys. Rev. D **85**, 032002 (2012). (**Di Giovanni,** co-editor, **Gartner, Hugon, Kropivinitskaya**, contributions).
25. CMS Collaboration, Measurement of the inclusive W and Z production cross sections in pp colisions at s = 7 TeV with the CMS experiment, JHEP10(2011)132 (**de Gruttola** – contributor)
26. CMS Collaboration, "Measurement of the Drell-Yan Cross Section (ds/dM) in pp Collisions at sqrt{s} = 7 TeV", arXiv:1010.5994, Phys. Lett. B695(2011), 424.
27. CMS Collaboration, "Search for new physics with same-sign isolated di-lepton events with jets and missing transverse energy at the LHC", JHEP 06 (2011), 077. (**Korytov** – co-editor, **Remington, Dobur**, contributors)
28. CMS Collaboration, "Search for Resonances in the Dilepton Mass Distribution in pp Collisions at $\sqrt{s}$ = 7 TeV", arXiv:1103.0981, JHEP 05(2011) ,093.
29. CMS Collaboration, "First Measurement of W+W− Production and Search for Higgs Boson in pp Collisions at $\sqrt{s}$ = 7 TeV", , arXiv:1102.5429, Phys. Lett. B699 (2011), 25.
30. CMS Collaboration) "Prompt and non-prompt J/psi Production in pp collisions as sqrt(s) = 7 TeV. arXiv:1011.4193, Eur. Phys. J. C71 (2011), 1575.
31. CMS Collaboration, "Measurement of the charge ratio of atmospheric muons with the CMS detector", Physics Letters B 692 (2010) 83-104, 22 pp.

Public results (CMS Physics Analysis Summaries and CMS Notes):

We note that in the CMS Collaboration "editor" is the title given to the designated coordinator of the analysis, and typically implies that, in addition, the editor's colleagues are central to the analysis. The review committee are chosen from those who are considered educated in the subject but are not performing the exact analysis in question. In cases when neither role is mentioned members of the UF group contributed greatly to the analysis.

1. "Properties of the Higgs-like boson in the decay H to ZZ to 4l in pp Collisions at sqrt(s) = 7 and 8 TeV" HIG-13-002 (**Drozdetskiy** – co-editor)

2. "Search for Supersymmetry in pp Collisions at sqrt(s) = 8 TeV in events with three leptons and at least one b-tagged jet." SUS-13-008. (**Shchutska** – co-editor)

3. "Updated results on the new boson discovered in the search for the standard model Higgs Boson in the H to ZZ to 4l channel in pp collisions at sqrt(s)=7 and 8 TeV". HIG-12-041

4. "Observation of a new boson with a mass near 125 GeV", CMS Physics Analysis Summary HIG-12-020, ICHEP 2012 (**Korytov** – co-editor)

5. “Evidence for a new state in the search for the standard model Higgs boson in the $H \rightarrow ZZ \rightarrow 4l$ channel in pp collisions at sqrt(s) = 7 and 8 TeV”, CMS Physics Analysis Summary HIG-12-016, ICHEP 2012 (**Drozdetskiy** – co-editor)
6. “Search for the standard model Higgs boson produced in association with W or Z bosons, and decaying to bottom quarks (ICHEP 2012)”, CMS Physics Analysis Summary HIG-12-019 (**Konigsberg** – editor)
7. “Search for a Higgs boson produced in association with b quarks and decaying into a b-quark pair”, CMS Physics Analysis Summary HIG-12-026 (**Konigsberg** – review committee chair)
8. “Search for Higgs bosons in pp collisions at sqrt(7) =7 and 8 TeV in the context of four-generation and fermiophobic models”, CMS Physics Analysis Summary HIG-12-013
9. “Updated Search for New Physics in Highly Boosted Z0 Decays to Dimuons in pp Collisions at $\sqrt{s}$ = 7 TeV”, EXO-11-025 (May 15, 2012) (**Di Giovanni** – editor)
10. “Search for direct EWK production of SUSY particles in multi-lepton modes with 8 TeV data”, CMS Physics Analysis Summary CMS PAS SUS-12-022
11. “Search for new physics in events with same-sign dileptons and b-tagged jets in pp collisions at sqrt(s) = 8 TeV, CMS Physics Analysis Summary PAS SUS-12-017
12. “Search for supersymmetry in events with same-sign dileptons and b-tagged jets with 8 TeV data”, CMS Physics Analysis Summary PAS SUS-12-029
13. “Search for electroweak production of charginos and neutralinos using leptonic final states in pp collisions at sqrt(s) = 7 TeV”, CMS Physics Analysis Summary PAS SUS-12-006
14. “Observation of $Z \rightarrow 4l$ decays in pp collisions at sqrt(s) = 7 TeV”, CMS Physics Analysis Summary SMP-12-009 (March 14, 2012) (**Drozdetskiy** – editor)
15. “Measurement of Spin Correlations in ttbar production” CMS PAS TOP-12-004 (**Mitselmakher** – review committee member)
16. "Combined results of searches for a Higgs boson in the context of the standard model and beyond-standard models", CMS Physics Analysis Summary HIG-12-008 (March 7, 2012) (**Korytov** -- co-editor)
17. "Determination of the Top Quark Mass from the ttbar Cross Section at $\sqrt{s}$ = 7 TeV", CMS Physics Analysis Summary TOP-11-008 (December 24, 2011) (**Korytov** -- review committee chair)
18. "Search for the Standard Model Higgs Boson decaying to Bottom Quarks", CMS Physics Analysis Summary HIG-11-031 (December 13, 2011) (**Konigsberg** -- editor)
19. "Combination of CMS searches for a Standard Model Higgs boson", CMS Physics Analysis Summary HIG-11-032 (December 13, 2011) (**Korytov** -- co-editor)
20. "Search for the Higgs boson in the $H \rightarrow ZZ \rightarrow 2l2\nu$ channel in pp collisions at $\sqrt{s}$ = 7 TeV", CMS Physics Analysis Summary HIG-11-026 (December 13, 2011) (Drozdetskiy -- co-editor, **Konigsberg**-review committee chair)
21. "Combination of CMS searches for a Standard Model Higgs boson", CMS Physics Analysis Summary HIG-11-032 (December 13, 2011) (**Korytov** -- co-editor)
22. "Search for the Higgs boson in the $H \rightarrow ZZ \rightarrow 2l2\nu$ channel in pp collisions at $\sqrt{s}$ = 7 TeV", CMS Physics Analysis Summary HIG-11-026 (December 13, 2011) (**Drozdetskiy** -- co-editor, **Konigsberg --**review committee chair)

23. "Search for a Standard Model Higgs Boson in the Decay Channel H→ZZ→4l, CMS Physics Analysis Summary HIG-11-025 (December 13, 2011)
24. "Combination of top quark pair production cross section measurements", CMS Physics Analysis Summary TOP-11-024 (November 23, 2011) (**Korytov** -- review committee chair)
25. ATLAS and CMS Collaborations, "Combined Standard Model Higgs boson searches with up to 2.3 fb−1 of pp collision data at sqrt(s) = 7 TeV at the LHC", ATLAS conference note ATLAS_CONF-2011-157, CMS Physics Analysis Summary HIG-11-023 (November 14, 2011) (**Korytov** -- co-editor)
26. "Search for the Standard Model Higgs Boson decaying to Bottom Quarks and Produced in Association with a W or a Z Boson", CMS Physics Analysis Summary HIG-11-012 (August 27, 2011) (**Konigsberg** -- editor)
27. "Search for standard model Higgs boson in pp collisions at sqrt(s) = 7 TeV and integrated luminosity up to 1.7 fb^{-1}", CMS Physics Analysis Summary HIG-11-022 (August 22, 2011) (**Korytov** -- co-editor)
28. "Search for the Higgs boson in the H→ZZ→2l2 ν channel in pp collisions at $\sqrt{s}$ = 7 TeV", CMS Physics Analysis Summary HIG-11-016 (August 22, 2011) (**Drozdetskiy** -- co-editor)
29. "First measurement of the ttbar production cross section in the dilepton channel with tau leptons in the final state in pp collisions at $\sqrt{s}$=7 TeV", CMS Physics Analysis Summary TOP-11-006 (July 27, 2011) (**Korytov** -- review committee chair)
30. "Search for new physics with same-sign isolated dilepton events with jets and missing energy", CMS Physics Analysis Summary SUS-11-010 (July 23, 2011) (**Dobur**, **Remington** -- co-editors)
31. "Search for standard model Higgs boson in pp collisions at sqrt(s) = 7 TeV", CMS Physics Analysis Summary HIG-11-011 (July 23, 2011) (**Korytov** -- co-editor)
32. "Search for the Higgs boson in the H→ZZ→2l2 ν channel in pp collisions at $\sqrt{s}$ = 7 TeV", CMS Physics Analysis Summary HIG-11-005 (July 22, 2011) (**Drozdetskiy** -- co-editor, **Konigsberg** -- review committee chair)
33. "Search for the charged Higgs boson with H+ → τ+ν decay mode in top quark decays", CMS Physics Analysis Summary HIG-11-008 (July 22, 2011) (**Korytov** -- review committee chair)
34. "Interpretation for searches for supersymmetry" CMS Physics Analysis Summary SUS-11-013, (**Yelton** -- review committee member)
35. ATLAS and CMS Collaborations, "Procedure for the LHC Higgs boson search combination in Summer 2011", ATL-PHYS-PUB-2011-11, CMS NOTE-2011/005 (August 26, 2011) (**Korytov** -- co-editor)
36. "Search for the charged Higgs boson in the eτ and μτ dilepton channels of top quark pair decays in pp collisions at $\sqrt{s}$=7 TeV", CMS Physics Analysis Summary HIG-11-002 (March 17, 2011) (**Korytov** -- review committee chair)
37. "Search for a narrow spin-2 resonance decaying to Z vector bosons in the semileptonic final state", CMS-PAS-EXO-11-102 (**Mitselmakher** – review committee member).
38. "Search for new physics with same-sign isolated di-lepton events with jets and missing transverse energy at the LHC", CMS Physics Analysis Summary SUS-10-004. (**Korytov** -- co-editor)

39. “Measurement of Differential Cross Sections for Z Bosons at √s = 7TeV”, CMS Physics Analysis Summary EWK-10-010

40. “Search for New Physics in Highly Boosted Z0 Decays to Dimuons in pp Collisions at √s = 7 TeV”, CMS Physics Analysis Summary EXO-10-025.

41. “Measurement of the Drell-Yan Cross Section (ds/dM) in pp Collisions at sqrt{s} = 7 TeV”, CMS Physics Analysis Summary EWK-10-007.

42. "Performance of Methods for Data-Driven Background Estimation in SUSY Searches", CMS Physics Analysis Summary SUS-10-001.

43. “Missing Transverse Energy Performance in Minimum-Bias and Jet Events from Proton-Proton Collisions at sqrt{s} = 7 TeV”, CMS Physics Analysis Summary JME-10-004.

44. “Performance of Missing Transverse Energy Reconstruction in sqrt{s} = 900 and 2360 GeV pp Collision Data”, CMS Physics Analysis Summary JME-10-002.

45. “Performance of Jet Algorithms in CMS”, CMS-PAS-JME-07-003. (**Mitselmakher**, review committee member).

CDF Here we only list the latest papers on which UF group members contributed very significantly to the analysis. July 2010 – June 2013.

Published:

1. T. Aaltonen et al., The CDF Collaboration, “Search for resonant production of top-antitop decaying to jets in proton-antiptoton collisions at sqrt{s}=1.96 TeV”, Phys. Rev. D84.072003 (2011). **Oksuzian** and **Konigsberg** are the main authors.
2. T. Aaltonen et al., The CDF Collaboration, “Search for resonant production of top-antitop pairs in 4.8 fb-1 of integrated luminosity of proton-antiproton collisions at sqrt{s}=1.96 TeV”, Phys. Rev. D84.072004 (2011). **Goldschmidt** and **Konigsberg** are the main authors.
3. T. Aaltonen et al., The CDF Collaboration, “Search for Higgs Bosons Produced in Association with b-Quarks”, Phys. Rev. D85, 032005 (2012). **Konigsberg** chaired the analysis review committee.
4. T. Aaltonen et al., The CDF Collaboration, “Search for a heavy particle decaying to a top quark and a light quark in ppbar collisions at sqrt(s) = 1.96 TeV”, Phys. Rev. Lett. 108 (2012) 211805. **Goldschmidt** is one of the main authors.

5.2 Proceedings and Collaboration Reports

CMS: Here we list those Analysis Notes and Conference Reports with UF authors. Et al implies that there are, in addition, authors from other institutions. Alphabetical order is retained throughout.

GENERAL

1. **Acosta,** Results from the First Two Years of Operation of the LHC: the CMS Experiment CMS CR-2012/181

2. **Furic,** Evolution of the CMS Trigger System. CMS CR-2012/337

HIGGS

1. **Avery, Chen, Cheng, Drozedetskiy, Korytov,** *Matchev*, **Milenkovic, Mitselmakher, Rinkevicius, Snowball** et al., Measurement of the production and decay of a Higgs Boson in the four-lepton final State. CMS AN-2013/108
2. **Acosta, DiGiovanni, Hugon, Kropivnitskaya, et al,** Search for standard model Higgs boson production in the mu mu final state with the CMS experiment in pp cullusions at sqrt(s)=7 and 8 TeV. CMS AN-2012-459.
3. **Avery,** *Bourilkov*, **Chen, Cheng, Drozedetskiy,** *Gainer*, **Korytov,** *Matchev*, **Milenkovic, Mitselmakher, Rinkevicius, Snowball** et al., Observation of a new boson decaying to ZZ to 4l and measurements of its properties using Matrix Element Kinematic Discriminant (MEKD). CMS AN-2012/409
4. **Das, Konigsberg.** A Z(bb)H(bb) Feasability Study. CMS AN-2012-398.
5. **Avery, Chen, Cheng, Drozedetskiy, Korytov,** *Matchev*, **Milenkovic, Mitselmakher, Rinkevicius, Snowball** et al., Updated results on the new boson discovered in the search for the standard model Higgs boson in the HH to ZZ to 4l channel in pp collisions at sqrt(s)=7 and 8 TeV. CMS AN-2012/367
6. **Acosta, Das, Fisher, Furic, de Gruttola, Konigsberg, Low,** et al, Data Driven b-Jet Validation for H-> bb, CMS AN-2012-266.
7. **Das, De Gruttola, Fisher, Furic, Hugon, Konigsberg** et al., Search for SM Higgs Boson in Produced in Association with W or Z and Decaying to Bottom Quarks (ICHEP2012). CMS AN-2012/181
8. **Avery, Bourilkov, Drozdetskiy, Chen, Cheng, Korytov,** *Matchev*, **Milenovic, Mitselmakher, Rinkevicius, Snowball et al.,** Search for the standard model Higgs Boson in the decay channel H to ZZ to 4l I pp Collisions.CMS AN-2012/141
9. **Avery, Bourilkov, Drozdetskiy, Chen, Cheng, Korytov,** *Matchev*, **Milenovic, Mitselmakher, Rinkevicius, Snowball et al.,** First Observation of Z to 4l Production in pp collisions at sqrt(s)=7 TeV. CMS AN-2012/054
10. **Drozdetskiy, Chen, Korytov, Snowball, Mitselmakher et al.,** Search for the Higgs Boson in the H to ZZ to 2l2nu Channel in pp Collisions at sqrt(s)=7 TeV with 2011 Data from CMS. CMS AN-2011/453
11. **Das, De Gruttola, Fisher, Furic, Konigsberg** et al., Update of Search for SM Higgs Boson in VH(bb), Using 5/fb of 7 TeV Collision data. CMS AN-2011/430
12. **Avery, Drozdetskiy, Chen, Cheng, Korytov, Milenovic, Mitselmakher, Rinkevicius, Snowball** et al., Search for a Higgs Boson in the H to ZZ to 4l Channel using the 2010/2011 Dataset. CMS AN-2011/385
13. **Avery, Chen, Drozdetskiy, Korytov, Mitselmakher, Snowball.,** Look-elsewhere effect in the H to ZZ to 4l Channel. CMS AN-2011/368
14. **Korytov, Chen et al.,** Procedure for the LHC Higgs Boson Search Combination in Summer 2011. CMS AN-2011/298
15. **Das, De Gruttola, Fisher, Furic, Konigsberg** et al., Search for the Standard Model Higgs Boson Produced in Associations with a W or Z boson and Decaying to Bottom Quarks. CMS-AN-2011/240
16. **Avery, Chen, Drozdetskiy, Korytov, Mitselmakher, Snowball,** A Complete Model of the Four-Lepton Invariant Mass Distributions for H to ZZ to 4l and ZZ to 4l Events. CMS AN-2011/201

17. **Chen, Drozdetskiy, Korytov, Mitselmakher, Snowball et al.,** Search for the Higgs Boson in the H to ZZ to 2l2nu Channel in pp Collisions at sqrt(s)=7 TeV. CMS AN-2011/119
18. **Drozdetskiy, Goldberg, Korytov, Mitselmakher, Pakhotin, Sellers, Skhirtladze, Snowball et al.** Search Strategy for the Higgs Boson in the ZZ* decay channel at sqrt(s) = 10 TeV with the CMS Experiment. CMS AN-2010/237

SUSY

1. **Dobur, Korytov,** *Matchev,* **Mitselmakher, Muniz, Shchutska, Skhirtladze, Yelton et al,** Search for new physics with same-sign dilepton events in CMS using the full 2012 data, CMS AN-2013/051.
2. **Dobur, Muniz, Shchutska, Skhirtladze et al,** Combinations and interpretation of the search for new physics in same-sign dileptons with and without bjets and MET in the full 2012 dataset. CMS AN-2013/086
3. *Allen*, **Dobur, Korytov,** *Matchev,* **Mitselmakher Shchutska, Skhirtladze, Yelton et al,** Search for New Physics using Mulit-Leptonic Signatures with b-tagged Jets and Missing Energy. CMS AN-2012/433.
4. *Allen,* **Dobur, Korytov,** *Matchev,* **Mitselmakher Shchutska, Skhirtladze, Yelton.** Data-driven Estimation of non-prompt lepton backgrounds for SUSY searches. CMS AN-2012/425.
5. *Allen*, **Dobur, Korytov**, *Matchev*, **Mitselmakher, Shchutska, Skhirtladze, Yelton.** Data-driven estimation of non-prompt lepton backgrounds for SUSY searches. CMS AN-2012/409.
6. **Dobur, Korytov,** *Matchev,* **Mitselmakher, Muniz, Shchutska, Skhirtladze, Yelton et al,** Interpretation of the Same-Sign di-leptons with bjets and MET search for HCP. CMS AN-2012/373.
7. **Dobur, Korytov,** *Matchev,* **Mitselmakher, Muniz, Shchutska, Skhirtladze, Yelton et al,** Update on the Search for New Physics with Same-Sign di-leptons, b-jets and MET. CMS AN-2012/353.
8. **Chen, Dobur, Korytov**, *Matchev*, **Mitselmakher, Muniz, Remington, Skhirtladze, Yelton, et al** Search for Direct Electroweak Production of Charginos and Neutralinos with the tri-Lepton Plus Missing Energy Final State at sqrt(s) = 8 TeV CMS AN-2012/248
9. **Chen, Dobur, Korytov**, *Matchev*, **Mitselmakher, Muniz, Remington, Skhirtladze, Yelton, et al** Interpretation of the Same-Sign di-leptons with bjets and MET Search CMS AN-2012/237
10. **Chen, Dobur, Korytov**, *Matchev*, **Mitselmakher, Muniz, Remington, Skhirtladze, Yelton, et al** Search for New Physics using Same-Sign di-leptons, b-tagged jets and MET CMS AN-2012/189
11. *Bourilkov*, **Kypreos, Furic et al.,** Measurement of the Differential and Double Differential Drell Yan Cross-Section in Proton-Proton Collisions at sqrt(s) = 7 TeV in Dimuon Channel. CMS AN-2012/063
12. **Chen, Dobur, Korytov,** *Matchev,* **Mitselmakher, Muniz, Remington, Skhirtladze, Yelton**, Search for Direct Electroweak Production of Charginos and Neutrilinos with the Tri-Lepton Plus Missing Energy Final State. CMS AN-2012/059
13. *Matchev*, **Remington,** Updated Templates for the Interpretation of Official CMS SUSY Results in the context of mSUGRA. CMS AN-2012/005,
14. **Chen, Dobur, Korytov**, *Matchev*, **Mitselmakher, Muniz, Remington, Skhirtladze, Yelton,** Search for sTop and sBottom production with Same-Sign di-Leptons, b-tagged jets and MET. CMS AN-2012/001

15. **Chen, Dobur, Korytov, Matchev, Mitselmakher, Muniz, Remington, Skhirtladze, Yelton,** Search for New Physics with Same-Sign Di-Leptons, Jets, and Missing Transverse Energy with 4.2 fb^{-1} of Data. CMS AN-2011/437
16. **Acosta, Avery,** *Bourilkov,* **Chen, Das, De Gruttola, Di Giovanni, Dobur, Drozdetskiy,** *Field,* **Fisher,** *Fu*, **Furic, Gartner, Hugon,** *Kim*, **Konigsberg, Korytov, Kropivnitskaya, Kypreos, Low,** *Matchev*, **Mitselmakher, Muniz, Remington, Rinkevicius,** *Scurlock,* **Sellers, Skhirtladze, Snowball, Wang, Yelton,** *Zakaria*, Search for New Physics with Same-Sign Di-Leptons, Jets, and Missing Transverse Energy using 2011 Data. CMS AN-2011/184
17. **Chen, Dobur, Furic, Korytov,** *Matchev,* **Mitselmakher, Muniz, Pakhotin, Remington, Skhirtladze, Wang, Yelton** Data-driven Measurement of the QCD Background to Same-sign Di-Lepton SUSY Searches with 34.7 pb-1 of 7 TeV Collision Data. CMS AN-2010/379
18. **Avery, Chen, Dobur, Drozdetskiy, Furic, Korytov,** *Matchev*, **Mitselmakher, Muniz, Pakhotin, Remington, Skhirtladze, Wang, Yelton** Data-driven Estimation of ttBar-like Standard Model Background Processes for Same-sign Di-Lepton signature. CMS AN-2010/378
19. **Avery, Chen, Dobur, Drozdetskiy**, Fu, **Furic**, Kim, **Korytov**, *Matchev*, **Mitselmakher, Muniz, Pakhotin, Remington, Skhirtladze, Wang, Yelton** Search for new physics with same-sign di-leptons, jets, and missing transverse energy in pp-collisions at 7 TeV. CMS AN-2010/372
20. **Acosta, Avery, Chen, Dobur, Drozdetskiy, Furic, Korytov,** *Matchev*, **Mitselmakher, Pakhotin, Remington, Skhirtladze, Wang, Yelton** CMS Discovery Potential for SUSY in Same-Charge Di-Lepton Inclusive Events in pp Collisions with sqrt(s) = 7 and 10 TeV. CMS AN-2010/238
21. **Dobur, Furic, Korytov,** *Matchev*, **Mitselmakher, Pakhotin, Remington, Skhirtladze, Wang, Yelton** Commissioning of a Measurement of Muon Isolation using b-jets at 7 TeV. CMS AN-2010/185
22. **Dobur, Furic, Korytov,** *Matchev,* **Mitselmakher, Pakhotin, Remington, Wang, Yelton** Commissioning the Data-driven Estimation of the QCD background in Di-Muon SUSY Searches with 7 TeV Collision Data. CMS AN-2010/170
23. **Dobur, Korytov,** *Matchev*, **Mitselmakher, Pakhotin, Remington, Yelton** Data-Driven Estimation of Muon Isolation Efficiency using b-jets from QCD. CMS AN-2010/169
24. **Dobur, Korytov,** *Matchev*, **Mitselmakher, Pakhotin, Remington, Wang, Yelton** Data-driven Estimation of the QCD Background in a SUSY Search with 2 Same-sign Muons. CMS AN-2010/058
25. **Dobur** Early LHC preparations for beyond-the-standard-model searches at CMS. CMS AN-2010/018

MUON PAIRS and STANDARD MODEL

1. **Acosta,** *Bourilkov*, **Di Giovanni, Kropivnitskaya,** et al., Measurement of the $Z/\gamma^* \rightarrow \mu^+\mu^-$ transverse momentum distribution in pp collisions at $\sqrt{s}$=8 TeV. CMS AN-2012/225
2. **Furic, Kypreos** et al., Search for High Mass Resonances Decaying to Muon Pairs at 1.8 TeV. CMS AN-2012/182
3. **Acosta,** *Bourilkov*, **Furic, Kypreos et al.** Search for High-Mass Resonances Decaying to Muon Pairs with Collisions Gathered at $\sqrt{s}$ = 7 TeV with 2011 Data. CMS AN-2011/47**3**
4. **Acosta,** *Bourilkov*, **DiGiovanni, Fisher, Furic, Gartner, Kotov, Kypreos et al.,** Search for High-Mass Resonances Decaying to Muon Pairs with Collisions Gathered at $\sqrt{s}$ = 7 TeV, CMS AN-2011/472

5. **Acosta,** *Bourilkov,* **DiGiovanni, Fisher, Furic, Gartner, Kotov, Kypreos, Piedra,** Search for High Mass Resonances Decaying to Muon Pairs with Collisions Gathered at $\sqrt{s} = 7$ TeV. CMS AN-2011/278
6. **Acosta, Bourilkov, DiGiovanni, Fisher, Furic, Gartner, Kotov, Kypreos, Piedra**, Search for High-Mass resonances Decaying to Muon Pairs with Collisions Gathered at $\sqrt{s} = 7$ TeV. CMS AN-2011/222
7. **Acosta, Amos, Avery,** *Bourilkov,* **Chen,** Cheng**, DeGruttola, DiGiovanni, Dobur, Drozdetskiy, Field, Fisher,** *Fu,* **Furic, Gartner, Hugon,** *Kim,* **Konigsberg, Korytov, Kotov, Kropivnitskaya, Kypreos,** *Matchev***, Mitselmakher, Muniz,** *Myeonghun, Rank,* **Remington,** *Scurlock***, Sellers, Skhirtladze, Snowball, Wang, Yelton,** *Zakaria*, Updated Search for New Physics using Highly Boosted Z decaying to Dimuons. CMS AN-2011/141
8. *Bourilkov,* **Fisher, Furic, Kypreos et al** Drell-Yan Differential Cross Section Measurement at 7 TeV in the Muon Channel CMS AN-2011/013
9. **Acosta**, *Bourilkov***, Furic, Gartner, Kotov, Kypreos et al** Measurement of the Z/gamma* -> mu+mu- transverse Momentum Distribution in pp Collisions as sqrt(s) = 7 TeV CMS AN-2010/444
10. **Acosta,** Bourilkov, **DiGiovanni, Fisher, Furic, Gartner, Kotov et al.** Search for New Physics Using Boosted Z Decaying to diMuons. CMS AN-2010/321
11. **Acosta,** *Bourilkov,* **DiGiovanni, Fisher, Furic, Garner, Kotov, Kypreos et al.** Search for High Mass Resonances Decaying to Muon Pairs with 15 pb-1 of Collisions Gathered at sqrt(s) = 7 TeV CMS AN-2010/317
12. **Drozdetskiy et al** Updated Measurements of the Inclusice W and Z Cross Sections at 7 TeV CMS AN-2010/264
13. **Acosta, Chen, Drozdetskiy, Furic, Korytov, Kypreos, Mitselmakher** Data-driven Estimation of di-Muon Background for Quarkonia Studies. CMS AN-2010/158
14. **Furic et al** Inclusive Total and Differential Production Cross-Section of J/Psi and b-hadron production in pp collisions at sqrt(s) = 7 TeV with the CMS experiment. CMS AN-2010/138
15. **Kypreos** Low-mass di-muons at CMS. CMS CR-2010/141
16. **Acosta, Chen, Drozdetskiy, Furic, Korytov, Kypreos, Mitselmakher** Data-driven Estimation of di-Muon Background for Quarkonia Studies. CMS AN-2010/158
17. **Acosta, Dobur**, Field**, Furic, Kotov, Kypreos,** Zakaria The Underlying Event in Proton-Proton Collisions at 900 GeV. CMS AN-2010/018

COSMIC RAYS and TECHNICAL

1. **Kypreos, Furic,** Measurement of the High-pt Momentum Scale with the Endpoint Method. CMS AN-2011/479
2. **Das, et al**. "Trigger strategies for Higgs searches". CMS AN-11-065
3. **Kypreos, Piedra, Mitselmakher et al** TeV Momentum scale in CRAFT data CMS AN-2010/190
4. **Wang et al** Type I and Type II CaloMET Perfomances in 7 TeV data. CMS AN-2010/131
5. **Acosta, DiGiovanni, Gartner, Remington, Yelton et al** Beam Halo Event Identification in CMS Using the CSCs, ECAL and HCAL. CMS AN-2010/111
6. **Dobur et al** Track-jets Results with sqrt(s) = 7 TeV pp Collisions. CMS AN-2010/079
7. **Dobur, Remington, Yelton** Magnetic Field Studies in the CMS Muon Endcap Using Cosmic Ray Data CMS AN-2010/057
8. **Kypreos, Piedra et al** Measurement of the Charge Asymmetry of Atmospheric Muons with the CMS Detector. CMS AN-2010/033
9. **Remington, Wang, Yelton et al** Commissioning of Uncorrected Calorimeter Missing Transverse Energy in Zero Bias and Minimum Bias Events. CMS AN-2010/029

10. **Chen, Avery,** *Bourilkov***, Furic,** Kim, **Kypreos, Pakhotin, Piedra, Schmitt** Upgraded Measurement of the Charge Ratio of Cosmic Rays Using Global Muon Reconstruction in CRAFT Data. CMS AN-2010/029
11. **Dobur et al** Commissioning of Track-Jets with 900 GeV and 2360 GeV data. CMS AN-2010/015
12. *Barashko***, Korytov,** *Levchenko, Madorsky***, Mitselmakher et al.** Commissioning of Muon Endcap Cathode Strip Chamber High-Voltage System. CMS IN-2010/032
13. **Remington, Wang et al** JetMet Data Quality Monitoring and Prompt Analysis of Jets in the First Collision data at CMS CMS AN-2010/007

COMPUTING

1. **Avery**, *Bourilkov, Kim, Fu*, et al, "Secure wide area network access to CMS analysis data using the Lustre filesystem", 2012 Conference of Computing in High Energy Physics, J. Phys. Conf. Ser., V331 (052034), Aug. 2012.
2. **Avery**, *Bourilkov, Kim, Fu*, et al, "Using virtual Lustre clients on the WAN for analysis of data from high energy physics experiments", J. Phys. Conference series, Aug. 2012.
3. **Avery**, *Bourilkov, Kim, Fu*, et al, "Utilizing Lustre file system with dCache for CMS analysis", 2010 Conference of Computing in High Energy Physics, J. Phys. Conf. Ser., V219 (062068), 2010.
4. **Avery**, *Bourilkov, Kim, Fu*, et al, "Wide area network access to CMS data using the Lustre™ filesystem", 2010 Conference of Computing in High Energy Physics, J. Phys. Conf. Ser., V219 (072049), 2010.
5. **Avery**, *Bourilkov, Kim, Fu*, et al, "Lustre filesystem for CMS Storage Element (SE)", 2010 Conference of Computing in High Energy Physics, J. Phys. Conf. Ser., V331 (052034), 2011.

5.3 Talks at conferences, colloquia, seminars

D. Acosta, "Results from the CMS Experiment after the First Year of LHC Operation", seminar at SUNY Stony Brook, November 8, 2010, NY, USA

D. Acosta, "CMS Status Report," Open meeting of the LHCC, CERN, September 21, 2011.

D. Acosta, "Results from the First Two Years of Operation of the LHC: the CMS Experiment," Eleventh Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2012), May 29 – June 3, 2012, St. Petersburg, FL, USA

P. Avery "LHC Physics, Distributed Computing and Open Science Grid", 2011 SESAPS meeting, Oct. 21, 2011, Virginia Tech, Roanoke, VA, USA

P. Avery "CMS Experiment Impact on Networks", Internet2 2011 Spring meeting, April 19, 2011, Washington, DC, USA

P. Avery "LHC Physics and Open Science Grid", Physics Colloquium, Apr. 12, 2011, Florida A&M, Tallahassee, FL, USA

P. Avery "LHC Physics and Open Science Grid", Miami Conference on High Energy Physics, Dec. 16, 2010, Ft. Lauderdale, FL, USA

P. Avery "LHC Physics and Open Science Grid", Biomed HPC Summit, Oct. 19, 2010, Harvard Medical School, Boston, MA, USA

M. Chen, "CMS BSM results", The 26th annual Lake Louise Winter Institute, 20-26 Feb 2011, Lake Louise AB, Canada

M. Chen, "CMS SM Higgs boson combination", Higgs Hunting 2012 workshop, July 18-20, 2012, Orsay, France

M. De Gruttola, "Measurement of W, Z and Top properties with CMS" at "La Thuile 2011: XXV Rencontres de Physique de La Vallee d'Aoste, 27 Feb-5 Mar 2011, La Thuile, Valle D'Aosta (Italy)"

M. De Gruttola, "Higgs results and prospect from CMS", **seminar** at Northwestern University, 23-05-11

M. De Gruttola, "Electroweak Results from CMS" at "44th Annual Fermilab Users' Meeting, 1-2 Jun 2011, Fermilab, Batavia, IL (United States)".

M De Gruttola, "Search for the Standard Model Higgs Boson Decaying to Bottom Quarks and Produced in Association with a W or a Z Boson" at HCP2011: HadronColliderPhysics Symposium 2011, 14-18 Nov 2011, Paris, Île-de-France (France)

M. De Gruttola, "Recent results from LHC experiments on the search of the standard model Higgs boson", seminar at Federico II U of Naples, MSA, 19-01-12

M. De Gruttola, "Search for Higgs decaying to bb", talk at the "LPC Physics forum", Fermilab 09-02-12

M. De Gruttola, "Search for Higgs to bb and tau-tau", talk at the USCMS meeting, Boulder, 05-17-12

M. De Gruttola, "Search for Higgs to bb and tau-tau", talk at the "Higgs Hunting Workshop", Orsay, 07-13-12.

D. Dobur, "Early LHC data preparations for SUSY searches at CMS", ICHEP, Paris, July 2010.

D. Dobur, "Top Quark Physics Results Using CMS Data at 7 TeV', 2nd International Conference on Particle Physics in Memoriam Engin Arik and Her Colleagues, June 2011.

D. Dobur, "Search for SUSY at CMS in Leptonic Final States", Physics at LHC conference, Perugia, June 2011.

D. Dobur, "2011 Highlights from the CMS experiment", End of the year CERN Council Meeting (LHC Jamboree), 16 December, 2011, CERN

D. Dobur, "Searches for Supersymmetry with leptons in the final state", DOE visit at CERN, 19 October 2011, CERN

D. Dobur, "Searching for Supersymmetry at the LHC: status and prospects", Invited talk at the Meeting of the Belgian Inter-University Attraction Pole, February 2012, Brussels

D. Dobur, "Searching for Supersymmetry: Status and road ahead ", Invited seminar at the University of Zurich, 14 March 2012, Zurich

D. Dobur, "Search for Chargino or Neutralino Production at CMS", SUSY12, Beijing, China, August 2012.

A. Drozdetskiy, "Searches for a Heavy Higgs with CMS", CIPANP 2012: Conference on the Intersections of Particle and Nuclear Physics (2012), 29 May-3 Jun 2012, Trumpf, St Petersburg, FL, USA

A. Drozdetskiy, "Status of the standard model Higgs boson searches", 10th April 2012, University of Florida, Gainesville, USA

A. Drozdetskiy, "Observation of Z->4l production in pp-collisions at 7 TeV with CMS", 16th Mar 2012, Fermi National Laboratory, Chicago, IL, USA

A. Drozdetskiy, "Standard Model Higgs Search", plenary talk at "April meeting of the American Physical Society", 31 Mar-3 Apr 2012, Atlanta, GA, USA

A. Drozdetskiy, "Standard Model Higgs Search: current status and latest updates", HEP seminar, April 6, 2011, University of Florida, Gainesville, USA

J. Gartner, "Measurement of the differential production cross section of Z bosons at 7 TeV," Meeting of the Division of Particles and Fields of the American Physical Society, Providence, Rhode Island, August 9-13, 2011.

J. Konigsberg, "Where in the World is the Higgs?". Invited plenary presentation at annual meeting of the Division of Particles and Fields of the Mexican Physical Society, Mexico City, May 2012.

J. Konigsberg, "Status and Prospects of the Higgs to bb Search". Invited presentation at the "New stretch of the Higgs Magnificent Mile" workshop, Chicago, May 2012.

J. Konigsberg, "Higgs to bb Search". Presentation at CMSDAS, Fermilab, January, 2012.

J. Konigsberg, "Higgs Results from the Tevatron" Invited presentation at the XXXI Physics in Collision conference, Vancouver, Canada, September 2011.

J. Konigsberg, "Understanding Elementary Particle Physics with High Energy Colliders", Invited Keynote plenary presentation at the 2011 Particle Accelerator Conference, New York, March, 2011.

J. Konigsberg, "Research at the High Energy Frontier", Invited presentation at the 2nd Congress of the Mexican High Energy Physics Network, Tlaxcala, Mexico, Jan 2011.

J. Konigsberg, "Collider Opportunities at Fermilab", Invited presentation at the VII Latin American Symposium in High Energy Physics, Valparaiso, Chile, Dec, 2010.

A. Korytov, "Higgs boson searches at the LHC", Workshop "LoopFest XII", May 13, 2013, Florida State University, Tallahassee FL, USA

A. Korytov, "CMS Higgs 126 GeV results", International workshop "The LHC Higgs Signal: Characterization, Interpretation and BSM Implications", April 22, 2013, University of California Davis, Davis CA, USA

A. Korytov, "Observation of a new boson with a mass near 125 GeV" Colloquium, August 30, 2012, University of Florida, Gainesville FL, USA

A. Korytov, "Tracking Detectors", three lectures at Fermilab-CERN HEP Summer School, August 6-8, 2012, Fermilab, Batavia IL, USA

A. Korytov, "Standard Model Higgs boson search at LHC" Colloquium, June 8, 2012, Jefferson Lab, Newport News VA, USA

A. Korytov, "Higgs boson: on the verge of discovery" Colloquium, March 6, 2012, University of Maryland, College Park MD, USA

A. Korytov, "Standard Model Higgs search at CMS", PITT PACC workshop "Light Higgs boson implications", January 13-15, 2012, Pittsburgh PA, USA

A. Korytov, "Where is the Higgs boson?" HEP seminar, January 10, 2012 University of Florida, Gainesville FL, USA

A. Korytov, "Standard Model Higgs search at CMS", Fermilab Wine & Cheese seminar, December 16, 2011, Fermilab, Batavia IL, USA

A. Korytov, "Standard Model Higgs search at LHC RDMS seminar", December 7, 2011, CERN, Geneva, Switzerland

A. Korytov, "Standard Model Higgs boson search at CMS", International workshop "Interpreting LHC Discoveries", Nov 7-11, 2011, Galileo Galilei Institute, Florence, Italy

A. Korytov, "Standard Model Higgs boson searches at CMS", International workshop "Higgs Days at Santander 2011", September 19-23, 2011, Santander, Spain

A. Korytov, "Standard Model Higgs search results from LHC", HEP seminar, September 6, 2011, University of Florida, Gainesville, USA

A. Korytov, "Combined results of SM Higgs boson search with the CMS Detector", International Europhysics Conference on High Energy Physics (EPS'11), July 21-27, 2011, Grenoble, France

A. Korytov, "Search for new physics in events with same-sign isolated di-leptons, jets, and missing transverse energy", HEP seminar, February 25, 2011, University of Florida, Gainesville FL, USA

A. Korytov, "Standard Model Higgs boson at CMS", International workshop "Higgs Days at Santander 2010", October 13-16 2011, Santander, Spain

A. Kropivnitskaya, "W and Z Studies at CMS," ICHEP 2012: International Conference on High Energy Physics, 4-12 Jul 2012, Melbourne, Australia

G. Mitselmakher, "Search for Higgs and Supersymmetry at the Large Hadron Collider", Colloquium, Florida International University, February 18, 2011

G. Mitselmakher, "Search for New Physics in Events with Same-Sign Isolated Di-Leptons with the CMS Experiment", Seminar, UCLA, March 9, 2011

G. Mitselmakher "Higgs searches at CMS", LISHEP 2011, Workshop on LHC, Present and Future, Rio de Janeiro, Brazil, July 4-10, 2011

G. Mitselmakher, "Searches for the Higgs and new physics at LHC", Seminar,Institute for Theoretical Physics and Astrophysics", Vilnius, Lithuania, September 27, 2011

G. **Mitselmakher,** "Higgs searches with the CMS detector at CERN", Seminar, University of Zurich, Switzerland, December 14, 2011.

G. **Mitselmakher,** "Searches for the Higgs boson with the CMS detector at LHC", Seminar, JINR, Dubna, Russia, May 17, 2012

G. **Mitselmakher,** "Higgs and SUSY searches with the CMS experiment at CERN", Seminar, Institute of Physics and Astronomy, Vilnius, Lithuania, May 22, 2012

G. **Mitselmakher,** "Observation of a narrow state with a mass of ~125 Gev with the CMS experiment at the LHC", Seminar, University of Sydney, Australia, July 24, 2012

G. **Mitselmakher,** "Observation of a narrow state with a mass of ~125 Gev with the CMS experiment at the LHC,", Seminar, LIGO Laboratory, Caltech, Pasadena, July 31, 2012

R. Remington, "Search for New Physics with Same-Sign Dileptons, Jets, and Missing Transverse Energy in pp Collisions at 7 TeV", APS Meeting Anaheim, California, 2011

R. Remington, "Search for Supersymmetry in Events with Same-Sign Di-Leptons and Missing Energy with the CMS Detector". HEP seminar at Cornell, March 2, 2012.

N. Skhirtladze, "Searches for Supersymmetry with Same-Sign Di-Leptons, Jets and Missing Transverse Energy with the CMS Detector" , LHCC Poster Session , 21 Mar 2012, Genève, Switzerland

M. Snowball, "Search for the Higgs boson at the CMS detector in the Higgs to ZZ to 4 lepton decay channel", APS Meeting, April 1-4, 2012, Atlanta, Georgia, USA

D. Wang, American Physical Society "Soft QCD Results from CMS, DPF meeting, Rhode Island, Aug 2011,

5.4 Recent Conference Organization

Implications of Higgs-like LHC signals

Korytov, Co-organizer, Aspen CO, August 11-29, 2013.

Les Houches Workshop Series "Physics at TeV Colliders"

Korytov, Co-organizer, Les Houches, France, June 3-21, 2013.

2013 Higgs Hunting Workshop

Konigsberg, Member International Advisory Committee, July 2013, Orsay, France.

2012 Tevatron Symposium

Konigsberg, Co-Chair Organizing Committee, June 2012, Fermilab, USA

2012 CERN-Fermilab Summer School

Konigsberg, Member International Advisory Committee, Summer 2012, Fermilab, USA

2012 Higgs Hunting Workshop

Konigsberg, Member International Advisory Committee, July 2012, Orsay, France
2011 CERN-Fermilab Summer School
Konigsberg, Member International Advisory Committee, Summer 2011, CERN, Switzerland
International Conference "Physics at LHC"
Mitselmakher, Conference Chair, Perguia, Italy, June 2011.
Advanced Studies Institute –" Symmetries and Spin" (SPIN-Praha-2011)
Mitselmakher, Co-chair of organizing committee, Prague, Czech Republic, May 2011.
XXIII International Symposium on Nuclear Electronics and Computing (NEC 2011)
Mitselmakher, Member of International Program Committee, Varna, Bulgaria, September 2011.
Topical Conference on Elementary Particles, Astrophysics, and Cosmology (MIAMI-2011).
Mitselmakher, LHC/Tevatron section organizer, Ft. Lauderdale, December 2011.
International Conference "Physics at LHC"
Mitselmakher, Conference Chair, Vancouver, Canada, June 2012
Advanced Studies Institute – "Symmetries and Spin" (SPIN-Praha-2012)
Mitselmakher, Co-chair of organizing committee, Prague, Czech Republic, July, 2012
Topical Conference on Elementary Particles, Astrophysics, and Cosmology (MIAMI-2012).
Mitselmakher, LHC/Tevatron section organizer, Ft. Lauderdale, December 2012.
International Conference "LHC-Physics (LHCP-2013)"
Mitselmakher, Conference Chair, Barcelona, Spain, May 2013
"Pontecorvo 100", Conference in honour of Bruno Pontecorvo for the bicentennial from the birth.
Mitselmakher, Member of the International Advisory Committee, Pisa, Italy, September 2013

5.5 HEP Committees

Acosta, Member, 2012 APS Panofsky Prize Committee

Konigsberg, Vice-chair, 2011 APS Tanaka Dissertation Award Committee

Konigsberg, Chair, 2012 APS Tanaka Dissertation Award Committee

Elementary Particle Theory & Phenomenology

at the University of Florida
Final Report - Task T

Rick Field, Konstantin Matchev, Pierre Ramond, Pierre Sikivie, Charles B. Thorn
(rfield@phys.ufl.edu, matchev@phys.ufl.edu, ramond@phys.ufl.edu,
sikivie@phys.ufl.edu, thorn@phys.ufl.edu)
Department of Physics
University of Florida

September 30, 2013

ABSTRACT

This is a final report from the elementary particle theory and phenomenology group (Task T) at the University of Florida for the DOE grant DE-FG02-97ER41029 that ended on June 30, 2013. Task T supported the research of R. Field, K. Matchev, P. Ramond, P. Sikivie, and C. Thorn during the period July 1, 2010 to June 30, 2013. Task T also supported the participation of R. Field in the CDF experiment and the participation of R. Field and K. Matchev in the CMS experiment.

OUTLINE

I. Introduction

The elementary particle theory and phenomenology DOE grant DE-FG02-97ER41029 (Task T) covered the activities the Particle Theory Group at the University of Florida and supported the research of R. Field, K. Matchev, P. Ramond, P. Sikivie, and C. Thorn during the period July 1, 2010 to June 30, 2013. Task T also supported the participation of R. Field in the CDF experiment and the participation of R. Field and K. Matchev in the CMS experiment. The Particle Theory Group conducts research at the forefront of high energy particle physics. The group covers a broad range of research activities ranging from fundamental theoretical issues to areas of immediate phenomenological importance. Some of the topics covered by the group include, but are not limited to: The light-cone structure of maximally supersymmetric theories, Field/String duality including the relation between QCD and string theory, studies of QCD and the "underlying event" at hadron colliders, collider signatures of new physics and their interpretation, the identity and distribution of dark matter, the origin of fermion and neutrino masses.

All faculty members of the group belong to the Institute for Fundamental Theory (IFT) in the Physics Department of the University of Florida. The IFT is an interdisciplinary center comprising of faculty members in high energy theory, condensed matter theory, cosmology-astrophysics, and mathematical physics. R. Field, K. Matchev and P. Sikivie also belong to the Institute of High Energy Physics and Astrophysics (IHEPA). IHEPA serves to facilitate collaborations of UF researchers in large scale experimental projects in the interdisciplinary area of Particle Physics and Astrophysics. The Particle Theory Group has a strong working relationship with IHEPA. R. Field is a member of CDF and both R. Field and K. Matchev are members of the CMS experiment. P. Sikivie is a member of ADMX (the Axion Dark Matter eXperiment) and RR (planned axion experiment at Fermilab). Task T (theory & phenomenology) consists of Task T1 (Theory) and Task T2 (Phenomenology). Task T1 supports the research of P. Ramond and C. Thorn, together with support for their students and postdoc and focuses on more theoretical issues. Task T2 supports the research of R. Field, K. Matchev, and P. Sikivie together with their students and postdocs and concentrates on collider phenomenology and astroparticle physics, including the participation of R. Field in CDF and R. Field and K. Matchev in CMS. The support of Task T has resulted in a deeper understanding of the fundamental particles and forces, and by understanding the data and in finding new directions for experimental exploration. We have also provided graduate and postdoctoral research training for the next generation of scientists.

II. Postdoctoral Fellows (*March 1, 2010 – June 30, 2013*)

Name	Length of Stay	Position After UF
P. Konar	2007-2010	Junior faculty, PRL, India
D. Belyaev	2008-2011	Teaching at SUNY/Albany
H. Tam	2010-2012	WorldQuant, Stamford, CT
G. Papathanasiou	2011-2013	Postdoc, Annecy
J. Gainer	2012-present	

III. Graduate Students (*March 1, 2010 – June 30, 2013*)

Name	Advisor	Graduation Date	Support or Current Position
P. Hearin	P. Ramond	*Ph.D. 2011*	Lecturer, junior college
J. Escobar	P. Ramond	*Ph.D. 2011*	Boeing, Seattle WA
Q. Yang	P. Sikivie	*Ph.D. 2011*	Junior faculty, Huazhong University of Science and Technology, China
M. Park	K. Matchev	*Ph.D. 2011*	Postdoc, CERN Theory Division
R. Remington (CMS)	Matchev/Yelton	*Ph.D 2011*	JHU Applied Physics Lab, MD
F. Rojas	C. Thorn	*Ph.D. 2012*	Postdoc, Sao Paolo, Brazil
G. Saranghi	K. Matchev	*Ph.D. 2012*	Postdoc, MPI Leipzig
M. Zakaria (CMS)	R. Field	*Expected 2013*	Full RA (Task T2)
Z. Zhang	P. Ramond	*Expected 2014*	Summer RA (Task T1)
J. Perez	P. Ramond	*Expected 2014*	Summer RA (Task T1)
D. Rank (CMS)	R. Field	*Expected 2014*	Partial RA (Task T2)
N. Banik	P. Sikivie	*Expected 2015*	Summer RA (Task T2)
D. Debnath	K. Matchev	*Expected 2017*	Summer RA (Task T2)
E. Todarello	P. Sikivie	*Expetced 2017*	Summer RA (Task T2)

Rick Field - Narrative

As a graduate student at Berkeley I worked in the Chamberlain-Segre experimental group and I worked on theoretical physics with my thesis advisor, J. D. Jackson. My first publication was an experimental paper [1] and my second publication was a theory paper [2]. I have continued to work on both theory and experiment. I joined CDF in January 1998. My first two years of working on CDF involved completing my "service work" obligations, which I did by doing simulations for the SVXII, ISL, and Layer 00 silicon detectors. I worked closely with Joe Incandela and David Stewart. My simulations for Layer 00 helped determine the final design and my plots were used in the upgrade proposal for Layer 00.

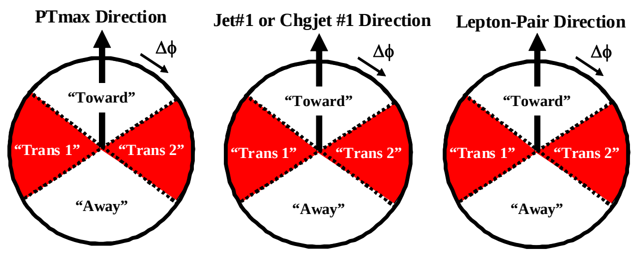


FIGURE 1: Illustration of correlations in azimuthal angle $\Delta\phi$ relative to (*left*) the direction of a "leading object" in the event. The relative angle $\Delta\phi = \phi - \phi_L$, where ϕ_L is the azimuthal angle of the "leading object" and ϕ is the azimuthal angle of a charged particle. The "toward" region is defined by $|\Delta\phi| < 60^o$ and $|\eta| < \eta_{cut}$, while the "away" region is $|\Delta\phi| > 120^o$ and $|\eta| < \eta_{cut}$. The two "transverse" regions $60^o < -\Delta\phi < 120^o$, $|\eta| < \eta_{cut}$ and $60^o < \Delta\phi < 120^o$, $|\eta| < \eta_{cut}$ are referred to as "transverse 1" and "transverse 2". The overall transverse region corresponds to combining the transverse-1 and transverse-2 regions. The "transMAX" ("transMIN") regions corresponds to the transverse region (transverse-1 or transverse-2) containing the largest (smallest) number of charged particles or to the region containing the largest (smallest) scalar p_T sum of charged particles.

I worked very hard to learn to perform my own analysis at CDF. From 1998 until 2004 I was an active member of the QCD group, the B group, the Jet Corrections subgroup, and the Top Mass subgroup within CDF. In January 2004, I was appointed convener of the CDF QCD Group and I focused on minimum bias collisions (MB) and the underlying event (UE) in hard scattering processes. Many years ago, R. Feynman, G. Fox, and I constructed one of the first QCD Monte-Carlo generators to simulate hadron-hadron collisions [3,4]. Hence, I have a good understanding of the QCD Monte-Carlo generators we use today such as PYTHIA [5] and HERWIG [6] and I know their limitations. I have worked to test and improve the QCD Monte-Carlo models. The goal is to accurately simulate, on an event-by-event basis everything the occurs in a hadron-hadron collision. To do this one must, not only, do a good job describing the hard scattering components of the collision, but in addition one must model the UE well. The UE consists of the beam-beam remnants (BBR) and the multiple parton interactions (MPI) that accompany a hard scattering. Figure 1 illustrates the "traditional" way of studying the UE by examining the "transverse" region as defined by a leading object. The QCD Monte-Carlo generators such as PYTHIA have parameters which may be adjusted to control the behavior of their event modeling. A specified set of these parameters that has been adjusted to better fit some aspects of the data is referred to as a tune [7,8]. I constructed all the CDF QCD Monte-Carlo Model tunes. The first PYTHIA 6.2 UE tune, Tune A, was determined by me by fitting the CDF Run 1 UE data [9] and my PYTHIA 6.2 Tune DW does a very nice job in describing both the CDF Run 1 and Run 2 UE data [10].

In 2006 Paolo Bartalini, Livio Fano, and I formed a group of people within CMS to study MB and the UE at the LHC (*i.e.* UEMB@CMS). In November 2010, we published the first LHC measurement of the UE at 900 GeV [13]. Later we published a second paper entitled, *Measurement of the Underlying Event Activity at the LHC at 7 TeV and Comparisons with 900 GeV* [15]. Figure 2 shows that my CDF PYTHIA 6.2 Tune DW did a fairly nice job of predicting the early CMS and ATLAS UE data. However, Tune DW did not reproduce perfectly all the features of the LHC data and after seeing the data, I construct several improved CMS LHC UE tunes. Figure 3 shows some of our CMS data at 900 GeV and 7 TeV compared with my PYTHIA 6.4 Tune Z1 [16,17].

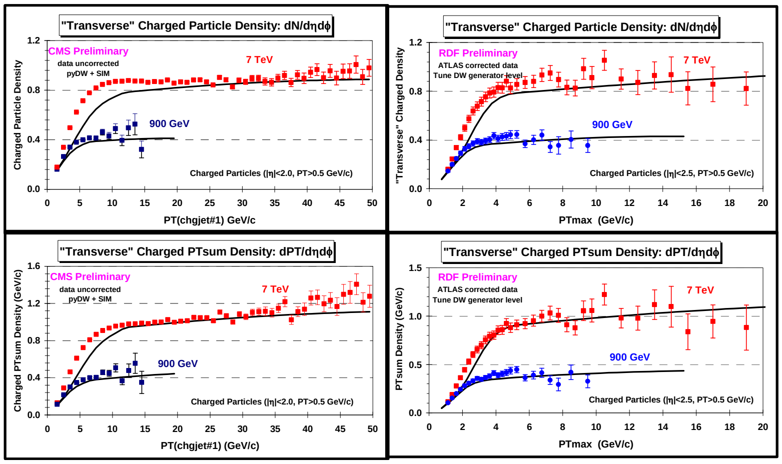


FIGURE 2: (*left column*) Early CMS preliminary data [13, 14] at 900 GeV and 7 TeV on the transverse charged particle density (*top left*) and the transverse charged PTsum density (*bottom left*) as defined by the leading charged particle jet (chgjet#1) for charged particles with p_T > 0.5 GeV/c and |η| < 2. The data are uncorrected and compared with PYTHIA Tune DW after detector simulation. (*right column*) Early ATLAS preliminary data [11] at 900 GeV and 7 TeV on the transverse charged particle density (*top right*) and the transverse charged PTsum density (*bottom right*) as defined by the leading charged particle (PTmax) for charged particles with p_T > 0.5 GeV/c and |η| < 2.5. The data are corrected and compared with PYTHIA Tune DW at the generator level.

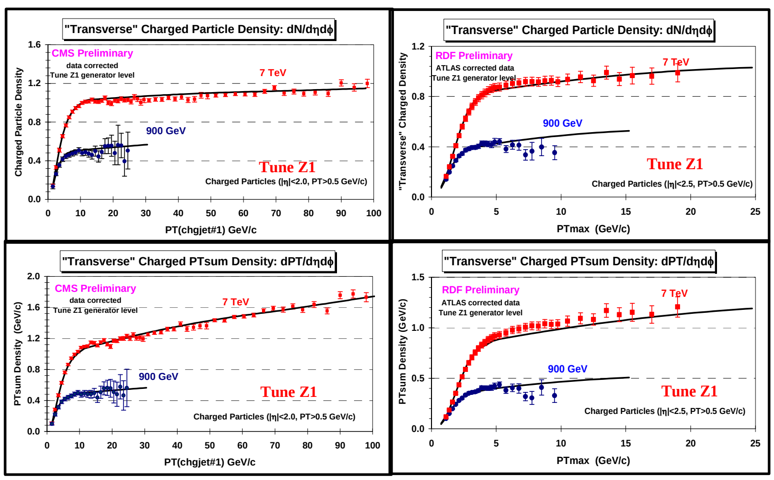


FIGURE 3: (*left column*) Recent CMS data [15] at 900 GeV and 7 TeV on the transverse charged particle density (*top left*) and the transverse charged PTsum density (*bottom left*) as defined by the leading charged particle jet (chgjet#1) for charged particles with p_T > 0.5 GeV/c and |η| < 2. (*right column*) ATLAS data [12] at 900 GeV and 7 TeV on the transverse charged particle density (*top right*) and the transverse charged PTsum density (*bottom right*) as defined by the leading charged particle, PTmax, as a function of PTmax for charged particles with p_T > 0.5 GeV/c and |η| < 2.5. The data are corrected to the particle level and compared with PYTHIA 6.4 Tune Z1 at the generator level.

Two things changed when we began to study the UE at the LHC. The center-of-mass energy changed, but also we began to study charged particles at very low p_T. The PYTHIA 6.2 Tune DW, which I created from CDF UE studies with p_T > 500 MeV/c at the Tevatron did a fairly good job in predicting the LHC UE data with p_T > 500 MeV/c at 900 GeV and 7 TeV. For p_T > 500 MeV/c the behavior of the UE at the LHC was roughly what we expected. However, there were more "soft" particles (*i.e.* p_T < 500 MeV/c) than predicted by the CDF Tevatron tunes. The CMS LHC PYTHIA 6.4 Tune Z1 does a very nice job describing both the CMS and ATLAS UE data at 900 GeV and 7 TeV. Tune Z1 uses the CTEQ5L parton distribution functions (same as Tune A and Tune DW) and we needed a good PYTHIA 6.4 tune that uses the newer CTEQ6L parton distributions. Therefore, I constructed the CMS PYTHIA 6.4 Tune Z2 which uses CTEQ6L. Later A. Knutsson, M. Zakaria and I constructed the CMS PYTHIA 6.4 Tune Z2* (CTEQ6L), which improved the energy dependence of Tune Z2 [18]. Tune Z2* is currently the best CMS PYTHIA 6 UE tune. It is the default PYTHIA 6 tune within CMS and is used in most CMS analyses.

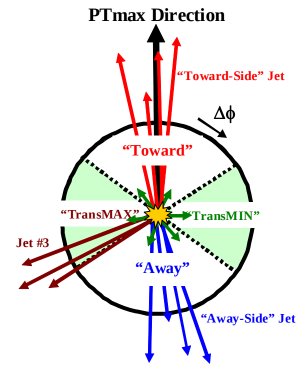


FIGURE 4: Illustration of the topology of a hadron-hadron collision in which a "hard" parton-parton collision has occurred. The "toward" region contains the leading "jet", while the "away" region, on the average, contains the "away-side" "jet". The "transverse" region is perpendicular to the plane of the hard 2-to-2 scattering and is very sensitive to the "underlying event". For events with large initial or final-state radiation the "transMAX" region defined in Fig. 1 will contain the third jet while both the "transMAX" and "transMIN" regions receive contributions from the MPI and beam-beam remnants (BBR). Thus, the "transMIN" region is very sensitive to the MPI and BBR, while the "transMAX" minus the "transMIN" (*i.e.* "transDIF") is very sensitive to initial and final-state radiation (ISR & FSR).

Just before the shutdown of the Tevatron, CDF collected about 12 million MB collisions at 300 GeV and about 54 million MB collisions at 900 GeV. This new Tevatron data together with the CDF data at 1.96 TeV allow for a detailed study of the energy dependence of MB and the UE. I have no students left working on CDF so I did the analysis myself. The MB part of my analysis involves producing the LPCC MB "common plots" at 300 GeV, 900 GeV, and 1.96 TeV and includes comparisons with LHC data at 900 GeV and 7 TeV. These "common plots" are a result of the LHC Physics Center at CERN (LPCC) MB&UE working group meetings [19]. The working group consists of theorists and experimenters who have suggested a series of MB plots that have been produced by ALICE, ATLAS, and CMS. These plots are very useful for tuning and improving the QCD Monte-Carlo models. The MB "common plots" consist of $dN/d\eta$, multiplicity and p_T distributions, and $<p_T>$ versus Nchg. Having these plots at 300 GeV, 900 GeV, 1.96 TeV, and 7 TeV will teach us a lot about the energy dependence of MB collisions and what we learn will help us do a better job of modeling the pile-up at the LHC at 13 TeV.

For the UE part of my analysis I look only at charged particles ($p_T > 0.5$ GeV, $|\eta| < 0.8$) and study the energy dependence of the charged particle and PTsum densities in the "transMAX", "transMIN, "transDIF", and "transAVE" regions as defined by the leading charged particle, PTmax. As shown in Figure 1 the "transMAX" ("transMIN") regions corresponds to the transverse region (transverse-1 or transverse-2) containing the largest (smallest) number of charged particles or to the region containing the largest (smallest) scalar p_T sum of charged particles. To form the "transMAX" and "transMIN" density one divides by the corresponding area in η-ϕ space. As illustrated in Figure 4, the "transMAX" region picks up the hardest initial or final-state radiation (ISR & FSR) while both "transMAX" and "transMIN" receive MPI and BBR contributions. Hence, "transMIN" is more sensitive to the MPI and BBR components of the UE, while "transDIF" is more sensitive to the ISR and FSR. The "transAVE" density is the average of the "transMAX" density and the "transMIN" density and is equal to the overall "transverse" density defined in Figure 1.

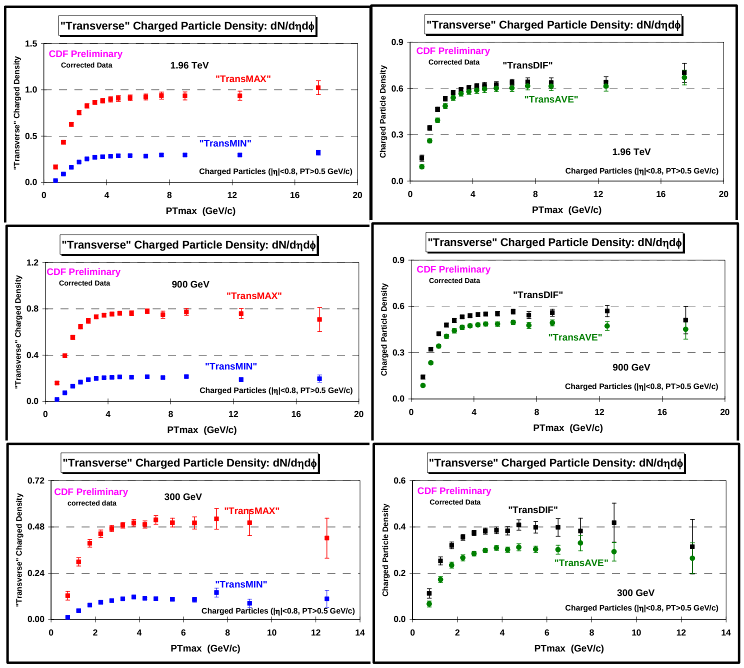


FIGURE 5: Data at 1.96 TeV (*top row*), 900 GeV (middle row), and 300 GeV (*bottom row*) on the "transMAX" and "transMIN" (*left column*) and "transAVE" and "transDIF" (*right column*) charged particle density as defined by the leading charged particle, PTmax, as a function of PTmax. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty. The charged particles have $p_T > 0.5$ GeV and $|\eta| < 0.8$.

Figure 5 shows the CDF data from my analysis at 1.96 TeV, 900 GeV, and 300 GeV on the "transMAX", "transMIN", and "transAVE", and "transDIF" charged particle density as defined by the leading charged particle, PTmax, as a function of PTmax. The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty. The "transMAX" region has much more activity than the "transMIN" region. At 1.96 TeV the "transAVE" and "transDIF" charge particle densities are almost equal which implies that "transMAX" is about three times "transMIN". However, at 300 GeV "transMAX" is more than three times "transMIN". This indicates that the four observables, "transMAX", "transMIN", and "transAVE", and "transDIF" all have a different energy dependence! As I will show, this data can be combined with CMS data to study the energy dependence of the UE more precisely than has been done in the past.

I have two students working with me on CMS, Mohammed Zakaria and Doug Rank. For the last 4 years Mohammed has been an active member of the UEMB@CMS group working on the UE. Last year Mohammed was awarded a Fermilab URA fellowship which allowed him to spend a year at the Fermilab LPC. Mohammed and I are performing the exact same UE analysis at CMS at 900 GeV and 7 TeV that I am doing at CDF at 300 GeV, 900 GeV, and 1.96 TeV. This includes not only producing the LPCC UE "common plots" (*i.e.* "transAVE"), but also a study of the "transMAX", "transMIN", and "transDIF" observables. So far the LHC UE analyses have only studied the "transAVE" observables.

Figure 6 shows CDF data at 300 GeV, 900 GeV, and 1.96 TeV (from my analysis) and CMS data at 7 TeV (from Mohammed's analysis) on the charged particle density in the "transMIN" and "transDIF" regions as defined by the leading charged particle, PTmax, as a function of PTmax. The data are corrected to the particle level and compared with PYTHIA 6.4 Tune Z2* at the generator level. The predictions of Tune Z2* for proton-proton collisions at 13 TeV are also shown. The "transMIN" charge particle density (more sensitive to MPI & BBR) increases much faster with center-of-mass energy than does the "transDIF" charge particle density (more sensitive to ISR & FSR). This can be seen clearly in Figure 7 which shows data at on the "transMIN", and "transDIF" charged particle density as defined by the leading charged particle, PTmax, for 5.0 < PTmax < 6.0 GeV/c plotted versus the center-of-mass energy (*on a log scale*). Tune Z2* predicts that the "transMIN" charged particle density increases by factor of around 6.6 in going from 300 GeV to 13 TeV, while the "transDIF" charged particle density is predicted to increase by only a factor of around 2.5. This is the first time we have seen the different energy dependences of these two components. Previously we only had information on the energy dependence of the "transAVE" (*i.e.* overall "transverse") charge particle density (see Fig. 3). What we are learning will allow for a deeper understanding of the BBR and MPI which will result in more precise predictions at the future LHC energies of 13 and 14 TeV.

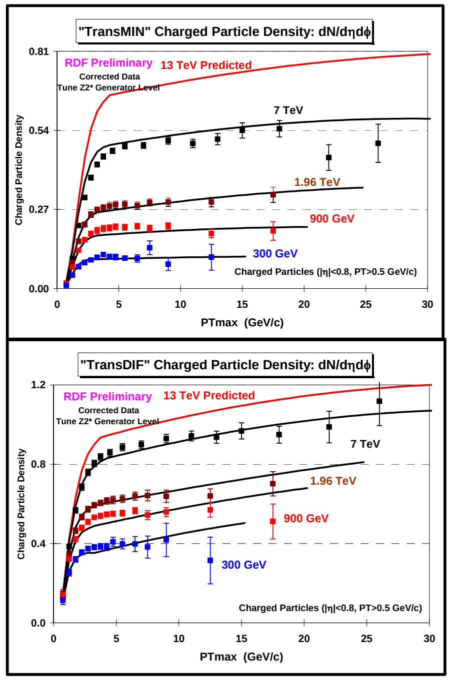


FIGURE 6: CDF data at 300 GeV, 900 GeV, and 1.96 TeV and CMS data at 7 TeV on the charged particle density in the "transMIN" (*top*) and "transDIF" (*bottom*) charge particle density as defined by the leading charged particle, PTmax, as a function of PTmax. The charged particles have $p_T > 0.5$ GeV and $|\eta| < 0.8$. The data are corrected to the particle level and compared with PYTHIA 6.4 Tune Z2* at the generator level. The predictions of Tune Z2* at 13 TeV are also shown.

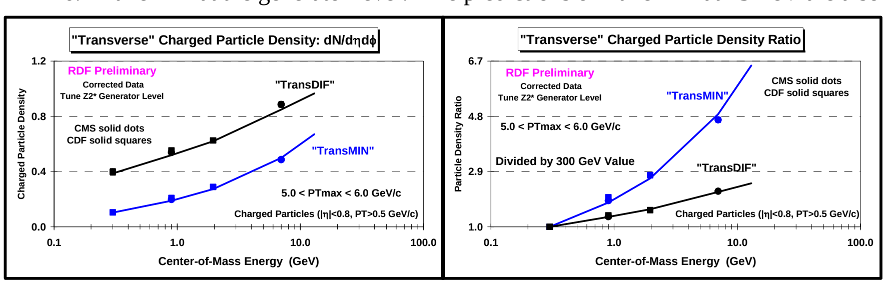


FIGURE 7: (*left*) CDF data at 1.96 TeV, 900 GeV, and 300 GeV and CMS data at 900 GeV and 7 TeV on the "transMIN", and "transDIF" charged particle density as defined by the leading charged particle, PTmax, for 5.0 < PTmax < 6.0 GeV/c plotted versus the center-of-mass energy (on a log scale). (*right*) Ratio of the data to the corresponding value at 300 GeV (*i.e.* 7 TeV divided by 300 GeV , 1.96 TeV divided by 300 GeV, 900 GeV divided by 300 GeV, and 300 GeV divided by 300 GeV which is equal to one) for the "transMIN" and "transDIF" charged particle density as defined by the leading charged particle, PTmax, for 5.0 < PTmax < 6.0 GeV/c plotted versus the center-of-mass energy (on a log scale). The data are corrected to the particle level with errors that include both the statistical error and the systematic uncertainty and are compared with PYTHIA 6.4 Tune Z2* at the generator level. The predictions of Tune Z2* at 13 TeV are also shown.

My graduate student Doug Rank is just getting started on CMS. Last year Doug was awarded an LPC Visiting Fellowship which allowed him to spend the summer of 2012 at the Fermilab LPC. He is working in the CMS Low p_T QCD group and we are studying the topological structure of the high multiplicity MB events at CMS. The CMS high multiplicity trigger was used to collect the events that showed evidence for "long-range same-side" correlations. However, we still know very little about the topological structure of these high multiplicity events. For example, what do the event shape variables look like? Also, what is the leading jet p_T distribution for high multiplicity events (*i.e.* Nchg > 120)? Does high multiplicity imply high p_T jets? Or is there a class of high multiplicity events that are "soft" (*i.e.* no high p_T)? I would like to know if the QCD Monte-Carlo models can describe high-multiplicity or if there is a source of high multiplicity that is not currently included in the QCD models. Doug's service work on CMS involves working with Darin Acosta and Ivan Furic on the muon trigger upgrade. He is developing new software which will control the upgraded electronics. The CMS software standard for electronics control ("online software") is the XDAQ framework. Doug has integrated the first electronics testing protocols for the upgraded muon trigger cards into XDAQ. He will continue integrating the electronics routines into the CMS standard protocols and will build the test stand tools for testing pre-production and production cards. The upgrade schedule calls for the new system to be commissioned for data taking in 2016. For comparison, the development and preparations of the existing system spanned a decade. In this highly accelerated schedule, it is critical that all commissioning and control tools be available, tested and validated within the next six months. Doug's work will produce these tools, which will be used and further built upon over the entire span of the upgrade commissioning and subsequent day-to-day data taking.

CMS recently expanded its Generator Group (GEN). In June 2013, I accepted a two year position as co-convener of the "Physics Comparisons & Generator Tunes", a subgroup of the CMS GEN Group. This new subgroup will lead the Monte-Carlo model (MC) tuning effort within CMS and play a leading role in data-MC comparisons, identifying areas where improvements in the generators are needed. Our first goal is to construct a PYTHIA 8 UE tune that is as good as the PYTHIA 6.4 Tune Z2* we are currently using. To do this we will use both the CDF and CMS UE data. In addition, in the future we plan to construct new and improved HERWIG++ and SHERPA tunes. With these improved tunes we will be able to make more accurate predictions for the LHC energies of 13 and 14 TeV. It is important to have the QCD Monte-Carlo models ready to go on day one when CMS starts taking data again in 2015.

References

1. *Backward np Scattering with a Polarized Target*, P. R. Robrish, O. Chamberlain, R. D. Field, R. F. Fuzesy, W. Gorn, C. C. Morehouse, T. Powell, S. Rock, S. Shannon, G. Shapiro, H. Weisberg and M. J. Longo, Phys. Letters **31B**, 617-620 (1970).
2. *Evidence on Duality and Exchange Degeneracy from Finite Energy Sum Rules: $K^- n$ to $\pi^- \Lambda$ and $\pi^+ n$ to $K^+ \Lambda$*, R. D. Field and J. D. Jackson, Phys. Rev. **D4**, 693-709 (1971).
3. *A Parameterization of the Properties of Quark Jets*, R. D. Field and R. P. Feynman, Nucl. Phys. **B136**, 1-76 (1978).
4. *A Quantum Chromodynamic Approach for the Large Transverse Momentum Production of Particles and Jets*, R. P. Feynman, R. D. Field and G. C. Fox, Phys. Rev. **D18**, 3320-3343 (1978).
5. T. Sjöstrand, Phys. Lett. **157B**, 321 (1985); M. Bengtsson, T. Sjöstrand, and M. van Zijl, Z. Phys. **C32**, 67 (1986); T. Sjöstrand and M. van Zijl, Phys. Rev. **D36**, 2019 (1987). T. Sjöstrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna and E. Norrbin, Computer Physics Commun. **135**, 238 (2001).
6. G. Marchesini and B. R. Webber, Nucl. Phys. **B310**, 461 (1988); I. G. Knowles, Nucl. Phys. **B310**, 571 (1988); S. Catani, G. Marchesini, and B. R. Webber, Nucl. Phys. **B349**, 635 (1991).
7. *PYTHIA Tune A, HERWIG, and JIMMY in Run 2 at CD*F, R. Field, Proceedings of the HERA-LHC Workshop, 2005. arXiv:hep-ph/0510198.
8. *CDF Run 2 Monte-Carlo Tunes*, R. Field, Proceedings of the 4th TeV4LHC Workshop, Fermi National Accelerator Laboratory, Batavia, IL, October 20-22, 2005. FERMILAB-CONF-06-408-E. arXiv:hep-ph/0610012.
9. *Charged Jet Evolution and the Underlying Event in Proton-Antiproton Collisions at 1.8 TeV*, The CDF Collaboration, Phys. Rev. **D65**, 092002, (2002).
10. *Studying the Underlying Event in Drell-Yan and High Transverse Momentum Jet Production at the Tevatron*, The CDF Collaboration, Phys. Rev. **D82**, 034001 (2010), arXiv:1003.3146.

11. *Track-Based Underlying Event Measurements in pp Collisions at 900 GeV and 7 TeV with the ATLAS Detector at the LHC*, The ATLAS Collaboration, ATLAS-CONF-2010-029.
12. *Measurement of Underlying Event Characteristics using Charged Particles in Collisions 900 GeV and 7 TeV with the ATLAS Detector*, The ATLAS Collaboration, Phys. Rev. **D83** (2011) 112001, arXiv:1012.0791.
13. *First Measurement of the Underlying Event Activity at the LHC with 0.9 TeV*, The CMS Collaboration, Eur. Phys. J. **C70**, 555-572, 2010, arXiv:1006.2083.
14. *Measurement of the Underlying Event Activity at the LHC at 7 TeV and Comparison with 0.9 TeV*, CMS Physics Analysis Summary, CMS-PAS-QCD-10-010, CERN, 2010.
15. *Measurement of the Underlying Event Activity at the LHC at 7 TeV and Comparison with 0.9 TeV*, The CMS Collaboration, J. High Energy Phys. **09** (2011) 109, arXiv:1107.0330.
16. *Early LHC Underlying Event Data - Findings and Surprises*, R. Field, arXiv:1010.3558, proceedings of the Hadron Collider Physics Symposium (HCP2010), August 23-27, 2010.
17. *Min-Bias and the Underlying Event at the LHC*, R. Field, arXiv:1110.5530, proceedings of the 51st Cracow School of Theoretical Physics: *The Soft Side of the LHC*, Zakopane, June 11 - 19, 2011, Acta Physica Polonica **B42**, 2631 (2011).
18. *The Underlying Event in Hadronic Collision*, R. Field, Annual Review of Nuclear and Particle Science, **62**, 427–457 (2012).
19. See the LPCC website at http://lpcc.web.cern.ch/LPCC/.

Konstantin Matchev: research narrative

1 Introduction

Over the past grant period, my research was mostly focused on the collider phenomenology of new physics Beyond the Standard Model (BSM). The specific query here is the following: once we observe a new physics signal in a channel with $\not{E}_T$, how do we systematically determine the fundamental properties of the particles responsible for this signal? The main goal of this research is to design methods for measuring the masses, spins and couplings of the new particles with as few theoretical assumptions as possible. In my experience, this often requires inventing suitable kinematic variables and studying their mathematical properties, then testing the applicability of the methods in realistic simulations.

More recently, I have turned my attention to the question of measuring the couplings of the newly discovered scalar resonance at CERN. I have become a regular participant in the UF-led analysis on Higgs to 4 leptons.

Personnel discussion. In the last three years, I led two PhD students to graduation (M. Park in 2011 and G. Sarangi in 2012) and supervised one postdoc (J. Gainer, 2012 - now). I also have a new, second-year student, Dipsikha Debnath, who is expected to graduate in 2017.

2 BSM phenomenology at hadron colliders

The dark matter problem motivates looking for BSM physics in events with $\not{E}_T$ at the LHC. Such events pose a great challenge in deciphering the exact nature of the new signal, since the parton-level center-of-mass energy ($\sqrt{\hat{s}}$) and longitudinal momentum (P_z) are a priori unknown. Furthermore, signatures with jets suffer from large SM QCD backgrounds, as well as a combinatorial problem related to the correct association of the jets with the colored partons resulting from the cascade decays of the new particles. Much of the theoretical work on BSM collider phenomenology in the past 5-10 years has been put into overcoming these challenges (for reviews, see [1, 2]).

2.1 New kinematic variables for discovery and/or mass measurements

Over the last 3-4 years, my group has been actively involved in redesigning the traditional methods for mass and spin measurements in SUSY cascade decay chains with missing particles (Fig. 1):

- We revisited the classic method of mass determination through invariant mass endpoints and studied the uniqueness of the solutions when one tries to solve for the actual masses (it was known that since the relevant functions are piecewise defined, multiple solutions can arise [3]). We proposed two solutions: first, using the shapes of the kinematic boundaries of *scatter plots in two variables* in place of the usual 1-dimensional distributions [4]; and making use of new, suitably defined invariant mass variables whose endpoint functions are *not* piecewise defined, and thus do not suffer from combinatorial ambiguities in the first place [5].

- By now the Oxbridge M_{T2} variable [6] has proven to be useful in many different contexts. Our group was among the first to recognize the importance of M_{T2} and to study its properties and potential applications beyond the original proposal of [6]. For example, we generalized M_{T2} to the case of different children particles [7]. We also proposed to apply M_{T2} exclusively to a subsystem of the whole event [8], an approach which yields additional information from the measurements of several M_{T2} endpoints instead of just one (in an already approved joint

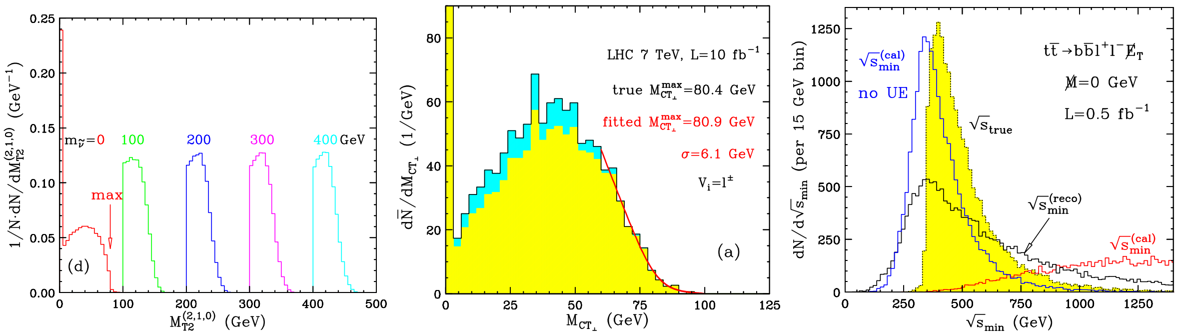


Figure 1: Kinematic distributions for a menagerie of variables recently proposed by the Florida BSM collider phenomenology group. From left to right: subsystem M_{T2} [8], $M_{CT_\perp}$ [11] and $\sqrt{\hat{s}}^{(reco)}_{min}$ [14]. Dilepton $t\bar{t}$ events have been used in all three cases.

CMS analysis between UF and Cornell [9], we used the top quark system to demonstrate the basic idea). We also proposed 1-dimensional analogues of M_{CT} [10] and M_{T2}, which we obtain by decomposing the measured transverse momenta onto a coordinate system defined by the direction of the measured upstream visible momentum. The resulting variables $M_{CT_\perp}$ [11] and $M_{T2_\perp}$ [12] have two important advantages: their endpoints do not depend on the value of the upstream visible momentum and their shapes are uniquely predicted theoretically.

- The variable which the UF group is perhaps most commonly credited with, is $\sqrt{\hat{s}}_{min}$ [13, 14]. It is a global and inclusive variable which has a clear physical meaning, makes full use of the information about the measured longitudinal momenta in the event, and retains the proper kinematic dependence on the masses of any invisible particles. In a recent review paper [15] we in fact demonstrated that virtually all useful invariant mass variables discussed in the literature are nothing but $\sqrt{\hat{s}}_{min}$ in disguise.

2.2 Spin discrimination

Traditional spin determination methods rely on the shape of the invariant mass distribution of a pair of SM particles from the SUSY decay chain [16, 17]. With my graduate students, we showed how to generalize the method and perform spin measurements without any a priori assumptions about the chirality of the fermion couplings [18]. Our method in fact allows for a simultaneous determination of the spins and masses of the new particles *and* the chiralities of their couplings. Our model-independent approach was adopted in subsequent studies by other groups [19, 20, 21, 22].

However, the invariant mass method for spin determination works only if the decay chain is sufficiently long, i.e. has at least two visible particles. The case of a single stage decay chain presents an infamous counterexample. Then, the invariant mass is formed by particles from the two opposite decay chains in the event, and the interpretation becomes challenging. In a recent paper [23], we studied the sensitivity to spins of nine different variables discussed in the literature, most notably $\cos\theta^*_{\ell\ell}$ [24]. An immediate application of these ideas is to measure the spin of the newly discovered 125 GeV resonance in the dilepton W^+W^- channel, which has the same event topology as the one studied in [23].

2.3 Event topology discrimination

Disambiguating the event topology of a generic new physics signal with missing energy is a difficult problem [25, 26, 27]. In a recent paper [28] we studied the shapes of the invariant mass distributions in the decay of a generic resonance to a certain number of visible particles and a certain (a priori unknown) number of invisible particles. In the simplest example of two visible daughter particles, we showed that the shape of their invariant mass distribution is sensitive to both the mass spectrum of the new particles, as well as the decay topology. The distribution can be simply categorized by its endpoint, peak location and curvature, which are typically sufficient to discriminate among the competing topologies. The fact that there are cases, in which a single invariant mass shape alone is sufficient to completely determine the new particle mass spectrum, including the overall mass scale, was certainly a pleasant surprise.

In another paper [29] with Rakhi Mahbubani and Myeonghun Park (both postdocs at CERN) we generalized the interpretation of the M_{T2} variable (and its measured kinematic endpoint) for the case of an arbitrary event topology (with an arbitrary number of invisible particles, each with an arbitrary mass). We also introduced a whole class variables which are 3+1 dimensional generalizations of the classic M_{T2} variable. These new variables can be used for improving the precision of mass measurements from kinematic endpoints, and may also help in disambiguating the event topology at hand.

2.4 The LHC inverse problem

The LHC inverse problem [30] is a very tough nut to crack. A typical approach involves a parameter scan over the huge SUSY parameter space [31, 32] and applying existing experimental constraints, including possibly additional measurements from ILC [33] and/or dark matter experiments [34]. In a recent paper [35] (featured as an "Editor's choice" in PRL) we tried a different, less quantitative, but more systematic approach. We started by considering all possible permutations of the masses of the superpartners and for each "hierarchy", we identified the dominant collider signatures at a hadron collider. (We define the dominant signature to be the production of the lightest colored superpartner, followed by any allowed decay with least suppressed branching fractions, see [35] for details). We then made a complete classification of all $9! = 362,880$ model hierarchies in terms of their dominant collider signatures. Our analysis was later generalized in [36], which included special treatment to the third generation squarks and sleptons.

3 Participation in the CMS experiment

I am an active participant in a number of ongoing CMS analyses.

3.1 Higgs identification

Higgs to four leptons. After the initial excitement surrounding the discovery of the 125 GeV boson, the next order of business is the determination of its properties (quantum numbers, etc.). The UF CMS group is a major contributor to one of the two major discovery channels, $H \to 4\ell$. This channel is also critical for measuring the spin and CP-parity of the resonance. At the request of the UF CMS group, with J. Gainer and M. Park, we developed an alternative tool, `MEKD`, for matrix element weighting of signal and background hypotheses [37]. The tool is based on an established program, MadGraph, has been validated against CalcHEP, and is being used in CMS.

With my postdoc J. Gainer and former student M. Park, and in collaboration with J. Lykken and S. Mrenna from Fermilab, we developed an efficient parameterization of the Higgs couplings to ZZ which takes into account the measured event rate. Our results were published in Physical Review Letters [38].

3.2 New physics searches

SUSY templates for presentation of LHC results. Last spring, our UF experimental postdoc Ronny Remington and I received an assignment from the CMS SUSY group conveners to properly map out the MSUGRA $M_0 - M_{1/2}$ parameter plane and create standard templates for the presentation of LHC results from SUSY searches (to be used by ATLAS and CMS as a common reference model). The assignment was completed [39] and SUSY searches from ATLAS and CMS are currently using those templates.

Like-sign dileptons. The like-sign dilepton signature was actively discussed at the start of Run II at the Tevatron [40, 41, 42], its main advantage being the improved signal acceptance at the cost of an acceptable increase in background. When I joined the University of Florida more than 10 years ago, I managed to convince our experimental group to pioneer the effort on this channel in CMS. Since then, the UF CMS group has been leading the like-sign dilepton analysis, which led to published CMS results with 35 pb^{-1} [43] and 5 fb^{-1} [44]. More recently, we also added b-tags in order to increase our sensitivity to new physics involving the third generation, and a published result with 4.98 fb^{-1} is also available [45].

Trileptons. The clean trilepton channel from chargino-neutralino pair production has long been known as a gold-plated mode for SUSY discovery at the Tevatron [41, 42] (see also [46, 47]), and the LHC is finally beginning to produce results in this channel as well. (The CMS paper on electroweakino is about to be made public.) For the next update of this analysis we are planning to apply a matrix element weighting method for reducing the SM WZ background. Taken together, the like-sign dilepton and the trilepton analyses represent my main involvement in CMS; I have been interacting daily with our CMS postdocs and students (as well as our collaborating partners from the UCLA CMS group) who were involved in these analyses.

Four tops from gluino pairs. Direct gluino pair production, followed by $\tilde{G} \to t\bar{t}\tilde{\chi}_1^0$ results in a characteristic 4 top signature (see, e.g. [48, 49]), which is currently under active investigation in CMS. With Brandon Allen, an UF undergraduate student, and Didar Dobur (UF postdoc and leptonic SUSY subgroup convener) we studied the resulting experimental signatures, reporting our results at a CMS 3rd Generation SUSY Working Group meeting [50]. Piggybacking on previous published searches in leptons plus b-jets [45], we considered various signatures in terms of the number of leptons N_{lep} and the number of tagged b-jets N_b.

Direct stop seach in the dilepton channel. Stop searches have been well-motivated ever since the days of the Tevatron [51]. With my collaborators from the CMS group at ETH Zürich, we initiated a direct stop search in the dilepton channel [52]. This is an extremely challenging signature, since the final state (2 b-jets, 2 opposite sign leptons and $\not{E}_T$) has large irreducible $t\bar{t}$ background. Nevertheless, we anticipated, based on our previous work [53], that the subsystem M_{T2} variable can be very useful for background discrimination. We have already made two presentations to the CMS 3rd Generation SUSY Working Group [52] and are now testing an alternative, matrix element based method for background rejection [54].

Mass measurements from endpoints in top dilepton events. My theoretical work on subsystem M_{T2} spawned a CMS analysis which attempted to measure the top, W and neutrino mass independently in top dilepton events, which look very SUSY-like (two decay chains, each ending with a missing particle) [55].

3.3 Dark matter

As a convener of the "CF4: Dark Matter Complementarity" subgroup of the Cosmic Frontier Working Group at Snowmass 2013, I was responsible for writing up the short and long summary reports [56].

4 Development of Monte Carlo simulation tools

I have a long standing interest in developing and teaching collider simulation tools. I am one of the main organizers of the MC4BSM series of workshops [57]. At the 6th MC4BSM workshop which took place at Cornell University, I was charged with the task of organizing computer tutorials on the most popular event simulation tools in high energy physics. The tutorials covered FeynRules, LanHEP, MadGraph, CalcHEP, Pythia 8, Herwig++, and Sherpa. We published a written version of the tutorial [58] which documents all activities at the Cornell workshop.

In 2011 I served as a Program director of the TASI Summer School in Boulder CO, where again I was charged with organizing daily tutorials on the most popular computer simulation programs. The computer tutorials at TASI 2011 covered CalcHEP and Pythia [59] and MicrOMEGAs. With my co-director Prof. T. Tait we were responsible for the timely publication of the TASI proceedings [60].

References

[1] A. J. Barr and C. G. Lester, *"A Review of the Mass Measurement Techniques proposed for the Large Hadron Collider,"* J. Phys. G G **37**, 123001 (2010) [arXiv:1004.2732 [hep-ph]].

[2] L.-T. Wang and I. Yavin, *"A Review of Spin Determination at the LHC,"* Int. J. Mod. Phys. A **23**, 4647 (2008) [arXiv:0802.2726 [hep-ph]].

[3] B. K. Gjelsten, D. J. Miller, 2 and P. Osland, *"Measurement of SUSY masses via cascade decays for SPS 1a,"* JHEP **0412**, 003 (2004) [hep-ph/0410303].

[4] M. Burns, K. T. Matchev and M. Park, *"Using kinematic boundary lines for particle mass measurements and disambiguation in SUSY-like events with missing energy,"* JHEP **0905**, 094 (2009) [arXiv:0903.4371 [hep-ph]].

[5] K. T. Matchev, F. Moortgat, L. Pape and M. Park, *"Precise reconstruction of sparticle masses without ambiguities,"* JHEP **0908**, 104 (2009) [arXiv:0906.2417 [hep-ph]].

[6] C. G. Lester and D. J. Summers, *"Measuring masses of semi-invisibly decaying particles pair produced at hadron colliders,"* Phys. Lett. B **463**, 99 (1999) [hep-ph/9906349].

[7] P. Konar, K. Kong, K. T. Matchev and M. Park, *"Dark Matter Particle Spectroscopy at the LHC: Generalizing M_{T2} to Asymmetric Event Topologies,"* JHEP **1004**, 086 (2010) [arXiv:0911.4126 [hep-ph]].

[8] M. Burns, K. Kong, K. T. Matchev and M. Park, *"Using Subsystem M_{T2} for Complete Mass Determinations in Decay Chains with Missing Energy at Hadron Colliders,"* JHEP **0903**, 143 (2009) [arXiv:0810.5576 [hep-ph]].

[9] N. Eggert, N. Mirman, B. Nachman, A. Dishaw, J. Alexander, M. Park and K. Matchev, *" Top quark mass determination by endpoint method"*, CMS analysis note AN-2010/316.

[10] D. R. Tovey, *"On measuring the masses of pair-produced semi-invisibly decaying particles at hadron colliders,"* JHEP **0804**, 034 (2008) [arXiv:0802.2879 [hep-ph]].

[11] K. T. Matchev and M. Park, *"A General method for determining the masses of semi-invisibly decaying particles at hadron colliders,"* Phys. Rev. Lett. **107**, 061801 (2011) [arXiv:0910.1584 [hep-ph]].

[12] P. Konar, K. Kong, K. T. Matchev and M. Park, *"Superpartner Mass Measurement Technique using 1D Orthogonal Decompositions of the Cambridge Transverse Mass Variable M_{T2},"* Phys. Rev. Lett. **105**, 051802 (2010) [arXiv:0910.3679 [hep-ph]].

[13] P. Konar, K. Kong and K. T. Matchev, *"$\sqrt{\hat{s}}_{min}$: A Global inclusive variable for determining the mass scale of new physics in events with missing energy at hadron colliders,"* JHEP **0903**, 085 (2009) [arXiv:0812.1042 [hep-ph]].

[14] P. Konar, K. Kong, K. T. Matchev and M. Park, *"RECO level $\sqrt{s}_{min}$ and subsystem $\sqrt{s}_{min}$: Improved global inclusive variables for measuring the new physics mass scale in $\not{E}_T$ events at hadron colliders,"* JHEP **1106**, 041 (2011) [arXiv:1006.0653 [hep-ph]].

[15] A. J. Barr, T. J. Khoo, P. Konar, K. Kong, C. G. Lester, K. T. Matchev and M. Park, *"Guide to transverse projections and mass-constraining variables,"* Phys. Rev. D **84**, 095031 (2011) [arXiv:1105.2977 [hep-ph]].

[16] C. Athanasiou, C. G. Lester, J. M. Smillie and B. R. Webber, *"Distinguishing Spins in Decay Chains at the Large Hadron Collider,"* JHEP **0608**, 055 (2006) [hep-ph/0605286].

[17] L.-T. Wang and I. Yavin, *"Spin measurements in cascade decays at the LHC,"* JHEP **0704**, 032 (2007) [hep-ph/0605296].

[18] M. Burns, K. Kong, K. T. Matchev and M. Park, *"A General Method for Model-Independent Measurements of Particle Spins, Couplings and Mixing Angles in Cascade Decays with Missing Energy at Hadron Colliders,"* JHEP **0810**, 081 (2008) [arXiv:0808.2472 [hep-ph]].

[19] M. Graesser and J. Shelton, *"Probing Supersymmetry With Third-Generation Cascade Decays,"* JHEP **0906**, 039 (2009) [arXiv:0811.4445 [hep-ph]].

[20] O. Gedalia, S. J. Lee and G. Perez, *"Spin Determination via Third Generation Cascade Decays,"* Phys. Rev. D **80**, 035012 (2009) [arXiv:0901.4438 [hep-ph]].

[21] F. Boudjema and R. K. Singh, *"A Model independent spin analysis of fundamental particles using azimuthal asymmetries,"* JHEP **0907**, 028 (2009) [arXiv:0903.4705 [hep-ph]].

[22] W. Ehrenfeld, A. Freitas, A. Landwehr and D. Wyler, *"Distinguishing spins in decay chains with photons at the Large Hadron Collider,"* JHEP **0907**, 056 (2009) [arXiv:0904.1293 [hep-ph]].

[23] L. Edelhauser, K. T. Matchev and M. Park, *"Spin effects in the antler event topology at hadron colliders,"* arXiv:1205.2054 [hep-ph].

[24] A. J. Barr, *"Measuring slepton spin at the LHC,"* JHEP **0602**, 042 (2006) [hep-ph/0511115].

[25] A. Rajaraman and F. Yu, *"A New Method for Resolving Combinatorial Ambiguities at Hadron Colliders,"* Phys. Lett. B **700**, 126 (2011) [arXiv:1009.2751 [hep-ph]].

[26] Y. Bai and H. -C. Cheng, *"Identifying Dark Matter Event Topologies at the LHC,"* JHEP **1106**, 021 (2011) [arXiv:1012.1863 [hep-ph]].

[27] P. Baringer, K. Kong, M. McCaskey and D. Noonan, *"Revisiting Combinatorial Ambiguities at Hadron Colliders with M_{T2},"* JHEP **1110**, 101 (2011) [arXiv:1109.1563 [hep-ph]].

[28] W. S. Cho, D. Kim, K. T. Matchev and M. Park, *"Cracking the dark matter code at the LHC,"* arXiv:1206.1546 [hep-ph].

[29] R. Mahbubani, K. T. Matchev and M. Park, *"Re-interpreting the Oxbridge stransverse mass variable MT2 in general cases,"* JHEP **1303**, 134 (2013) [arXiv:1212.1720 [hep-ph]].

[30] N. Arkani-Hamed, G. L. Kane, J. Thaler and L.-T. Wang, *"Supersymmetry and the LHC inverse problem,"* JHEP **0608**, 070 (2006) [hep-ph/0512190].

[31] C. F. Berger, J. S. Gainer, J. L. Hewett and T. G. Rizzo, *"Supersymmetry Without Prejudice,"* JHEP **0902**, 023 (2009) [arXiv:0812.0980 [hep-ph]].

[32] S. Sekmen, S. Kraml, J. Lykken, F. Moortgat, S. Padhi, L. Pape, M. Pierini and H. B. Prosper *et al.*, *"Interpreting LHC SUSY searches in the phenomenological MSSM,"* JHEP **1202**, 075 (2012) [arXiv:1109.5119 [hep-ph]].

[33] C. F. Berger, J. S. Gainer, J. L. Hewett, B. Lillie and T. G. Rizzo, *"General Features of Supersymmetric Signals at the ILC: Solving the LHC Inverse Problem,"* Phys. Rev. D **80**, 095018 (2009) [arXiv:0712.2965 [hep-ph]].

[34] B. Altunkaynak, M. Holmes and B. D. Nelson, *"Solving the LHC Inverse Problem with Dark Matter Observations,"* JHEP **0810**, 013 (2008) [arXiv:0804.2899 [hep-ph]].

[35] P. Konar, K. T. Matchev, M. Park and G. K. Sarangi, *"How to look for supersymmetry under the lamppost at the LHC,"* Phys. Rev. Lett. **105**, 221801 (2010) [arXiv:1008.2483 [hep-ph]].

[36] H. Dreiner, W. Porod, F. Staub and A. Vicente, *"General MSSM signatures at the LHC with and without R-parity,"* arXiv:1205.0557 [hep-ph].

[37] P. Avery, D. Bourilkov, M. Chen, T. Cheng, A. Drozdetskiy, J. S. Gainer, A. Korytov and K. T. Matchev *et al.*, "Precision Studies of the Higgs Golden Channel H -¿ ZZ* -¿ 4l. Part I. Kinematic discriminants from leading order matrix elements," Phys. Rev. D **87**, 055006 (2013) [arXiv:1210.0896 [hep-ph]].

[38] J. S. Gainer, J. Lykken, K. T. Matchev, S. Mrenna and M. Park, "Spherical Parametrization of the Higgs Boson Candidate," Phys. Rev. Lett. **111**, 041801 (2013) [arXiv:1304.4936 [hep-ph]].

[39] K. Matchev and R. Remington, *"Updated templates for the interpretation of LHC results on supersymmetry in the context of mSUGRA,"* arXiv:1202.6580 [hep-ph].

[40] J. Nachtman *et al.* [CDF Collaboration], *"Study of a like sign dilepton search for chargino neutralino production at CDF,"* hep-ex/9902010.

[41] K. T. Matchev and D. M. Pierce, *"Supersymmetry reach of the Tevatron via trilepton, like sign dilepton and dilepton plus τ jet signatures,"* Phys. Rev. D **60**, 075004 (1999) [hep-ph/9904282].

[42] K. T. Matchev and D. M. Pierce, *"New backgrounds in trilepton, dilepton and dilepton plus τ jet SUSY signals at the Tevatron,"* Phys. Lett. B **467**, 225 (1999) [hep-ph/9907505].

[43] S. Chatrchyan *et al.* [CMS Collaboration], *"Search for new physics with same-sign isolated dilepton events with jets and missing transverse energy at the LHC,"* JHEP **1106**, 077 (2011) [arXiv:1104.3168 [hep-ex]].

[44] S. Chatrchyan *et al.* [CMS Collaboration], *"Search for new physics with same-sign isolated dilepton events with jets and missing transverse energy,"* Phys. Rev. Lett. **109**, 071803 (2012) [arXiv:1205.6615 [hep-ex]].

[45] S. Chatrchyan *et al.* [CMS Collaboration], *"Search for new physics in events with same-sign dileptons and b-tagged jets in pp collisions at sqrt(s) = 7 TeV,"* arXiv:1205.3933 [hep-ex].

[46] H. Baer, M. Drees, F. Paige, P. Quintana and X. Tata, *"Trilepton signal for supersymmetry at the Fermilab Tevatron revisited,"* Phys. Rev. D **61**, 095007 (2000) [hep-ph/9906233].

[47] V. D. Barger and C. Kao, *"Trilepton signature of minimal supergravity at the upgraded Tevatron,"* Phys. Rev. D **60**, 115015 (1999) [hep-ph/9811489].

[48] B. S. Acharya, P. Grajek, G. L. Kane, E. Kuflik, K. Suruliz and L. -T. Wang, *"Identifying Multi-Top Events from Gluino Decay at the LHC,"* arXiv:0901.3367 [hep-ph].

[49] T. Gregoire, E. Katz and V. Sanz, *"Four top quarks in extensions of the standard model,"* Phys. Rev. D **85**, 055024 (2012) [arXiv:1101.1294 [hep-ph]].

[50] B. Allen, D. Dobur, P. Everaerts, A. Korytov, K. Matchev, G. Mitselmakher, L. Muniz, L. Shchutska, N. Skhirtladze and J. Yelton, *"Optimization of Three Lepton and Same Sign Dilepton with b-Jets Searches in Context of Four Top Final State"*, talk given at the CMS 3rd Generation SUSY Working Group, August 8, 2012 (slides).

[51] R. Demina, J. D. Lykken, K. T. Matchev and A. Nomerotski, *"Stop and sbottom searches in Run II of the Fermilab Tevatron,"* Phys. Rev. D **62**, 035011 (2000) [hep-ph/9910275].

[52] H. Weber, F. Moortgat, L. Pape (ETH Zürich), K. Matchev (Florida), *"Search for direct stops using dileptons"*, talk given at the CMS 3rd Generation SUSY Working Group, July 20, 2012 (slides); H. Weber, F. Moortgat, L. Pape (ETH Zürich), K. Matchev (Florida), *"Dilepton stop search with M_{T2}"*, talk given at the CMS 3rd Generation SUSY Working Group, August 17, 2012 (slides).

[53] K. T. Matchev, F. Moortgat, L. Pape and M. Park, *"Precision sparticle spectroscopy in the inclusive same-sign dilepton channel at LHC,"* Phys. Rev. D **82**, 077701 (2010) [arXiv:0909.4300 [hep-ph]].

[54] J. Gainer, K. Matchev and M. Park, *"Weighing tops and stops with matrix elements",* in preparation.

[55] S. Chatrchyan *et al.* [CMS Collaboration], "Measurement of masses in the $t\bar{t}$ system by kinematic endpoints in pp collisions at $\sqrt{s}$ = 7 TeV," Eur. Phys. J. C **73**, 2494 (2013) [arXiv:1304.5783 [hep-ex]].

[56] D. Bauer, J. Buckley, M. Cahill-Rowley, R. Cotta, A. Drlica-Wagner, J. Feng, S. Funk and J. Hewett *et al.*, "Dark Matter in the Coming Decade: Complementary Paths to Discovery and Beyond," arXiv:1305.1605 [hep-ph].

[57] MC4BSM workshops (webpages).

[58] S. Ask, N. D. Christensen, C. Duhr, C. Grojean, S. Hoeche, K. Matchev, O. Mattelaer and S. Mrenna *et al.*, *"From Lagrangians to Events: Computer Tutorial at the MC4BSM-2012 Workshop,"* arXiv:1209.0297 [hep-ph].

[59] K. Kong, *"TASI 2011: CalcHEP and PYTHIA Tutorials,"* arXiv:1208.0035 [hep-ph].

[60] K. Matchev, T. Tait (Editors), *"TASI-2011: The Dark Secrets of the Terascale"*, Proceedings of the TASI 2011 summer school, Boulder CO, June 6 - July 1 2011.

Pierre Ramond: research narrative

During the grant period, I worked on two things. One was to continue determining if all the maximally supersymmetric superconformal theories can sustain interaction. One answer was in the negative, the theory in three dimensions with sixteen supersymmetries (paper with Belyaev and Hearin). The second was the (2,0) theory in six dimensions. I was able to show how to restrict its interactions by requiring that it reduces by Kaluza-Klein compactification to the super-Yang-Mills theory in five dimensions where the squared gauge coupling has inverse mass dimension. This was not sufficient to determine the (2,0) interactions, and it has not resulted in any publication.

The second line of research has been to examine the question of supersymmetry breaking in theories with a family group. In studying a toy model, my students and I were able to show a new twist. The Higgs family partners can set the boundary conditions on the squark renormalization group equations at some scale. At lower scales, the normal Higgs rule the evolution equations. With a family symmetry, the Yukawa couplings of the "normal" Higgs and the family partner Higgs are related by the family symmetry. This leaves us with a situation where the initial conditions and evolution of the RG equations are not independent. This is a new result which my students and I published. Since then we have been working on a realistic model where such an effect is present, in the hope it can lead to an understanding of squark mass degeneracies in the infrared. We are on the verge of publishing a long paper in the uses of this family group on unified quark and lepton masses.

Pierre Sikivie: research narrative

Over the past grant period, my research has focussed on two general areas. The first is axion cosmology and the structure of galactic halos, the second is axion detection. The work on axion detection is done for the most part in collaboration with ADMX, of which I am a member. Since that work is described in the Task N proposal, I focus on axion cosmology here.

One of the outstanding problems in science today is the identity of the dark matter of the universe [1]. The existence of dark matter is implied by a large number of observations, including the dynamics of galaxy clusters, the rotation curves of individual galaxies, the abundances of light elements, gravitational lensing, and the anisotropies of the cosmic microwave background radiation. The energy density fraction of the universe in dark matter is 23%. The dark matter must be non-baryonic, cold and collisionless. Particles with the required properties are referred to as 'cold dark matter' (CDM). The leading CDM candidates are weakly interacting massive particles (WIMPs) with mass in the 100 GeV range, axions with mass in the 10^{-5} eV range, and sterile neutrinos with mass in the keV range.

Based on the work that my collaborators and I have done over the past three or four years, I have come to the conclusion that at least some of the dark matter is axions. The argument has three steps. First, axions behave differently from the other forms of cold dark matter because they form a Bose-Einstein condensate [2]. Second, there is a tool to distinguish axion BEC from the other forms of CDM on the basis of observation, namely the study of the inner caustics of galactic halos. Third, the observational evidence for caustic rings of dark matter is consistent in every aspect with axion BEC[3], but not with the other forms of dark matter. I now elaborate these three steps.

1 Bose-Einstein condensation of cold dark matter axions

Cold dark matter axions are produced in the early universe [4] when the axion mass turns on during the QCD phase transtion, at time $t_1 \simeq 2 \cdot 10^{-7}$ sec $(f/10^{12}\ \text{GeV})^{\frac{1}{3}}$, where f is the axion decay constant. The zero-temperature axion mass is related to f by

$$m \simeq 6 \cdot 10^{-6}\ \text{eV}\ \frac{10^{12}\ \text{GeV}}{f} \quad . \tag{1}$$

The cold axions have number density

$$n(t) \sim \frac{4 \cdot 10^{47}}{\text{cm}^3} \left(\frac{f}{10^{12}\ \text{GeV}}\right)^{\frac{5}{3}} \left(\frac{a(t_1)}{a(t)}\right)^3 \tag{2}$$

where $a(t)$ is the cosmological scale factor. Because the axion momenta are of order $\frac{1}{t_1}$ at time t_1 and vary with time as $a(t)^{-1}$, the velocity dispersion of cold axions is

$$\delta v(t) \sim \frac{1}{mt_1} \frac{a(t_1)}{a(t)} \tag{3}$$

if each axion remains in whatever state it is in, i.e. if axion interactions are negligible. The average state occupation number of cold axions is then

$$\mathcal{N} \sim n \frac{(2\pi)^3}{\frac{4\pi}{3}(m\delta v)^3} \sim 10^{61} \left(\frac{f}{10^{12}\ \text{GeV}}\right)^{\frac{8}{3}} \quad . \tag{4}$$

That $\mathcal{N}$ is much larger than one tells us that the effective temperature of cold axions is much smaller than the critical temperature for Bose-Einstein condensation.

Bose-Einstein (BEC) may be briefly described as follows: if identical bosonic particles are highly condensed in phase space, if their total number is conserved and if they thermalize, most of them go to the lowest energy available state. The condensing particles do so because, by yielding their energy to the remaining non-condensed particles, the total entropy is increased. Eq. (4) tells us that the first condition is overwhelmingly satisfied. The second condition is also satisfied because all axion number violating processes, such as their decay to two photons, occur on time scales vastly longer than the age of the universe. The only condition for axion BEC that is not manifestly satisfied is thermal equilibrium.

Axions are in thermal equilibrium if their relaxation rate Γ is large compared to the Hubble expansion rate $H(t) = \frac{1}{2t}$. The relaxation rate Γ is given in the *particle kinetic* regime by

$$\Gamma \sim n\ \sigma\ \delta v\ \mathcal{N} \tag{5}$$

where σ is the relevant scattering cross-section. The particle kinetic regime is defined by the condition $\Gamma << \delta E$ where δE is the energy dispersion of the particles. Cold dark matter axions are however in the opposite regime: $\Gamma >> \delta E$ which we call the *condensed regime*. Thermalization in the condensed regime is discussed in detail in our recent paper [5]. We find that the relaxation rate of cold axions through their $\lambda\phi^4$ self-interactions is of order [2, 5]

$$\Gamma_\lambda \sim \frac{1}{4}\lambda\ n\ m^{-2} \quad . \tag{6}$$

The self-coupling strength is

$$\lambda = \frac{m^2}{f^2}\ \frac{m_d^3 + m_u^3}{(m_d + m_u)^3} \simeq 0.35\ \frac{m^2}{f^2} \tag{7}$$

where m_u and m_d are the masses of the up and down quarks. $\Gamma_\lambda(t)/H(t)$ is of order one at time t_1 but decreases as $t\ a(t)^{-3} \propto a(t)^{-1}$ afterwards [2, 5], implying that cold axions briefly thermalize as a result of their $\lambda\phi^4$ interactions when they are first produced during the QCD phase transition but, after this brief period of thermalization, the axions are decoupled again.

However the axions rethermalize later as a result of their gravitational self-interactions. Their relaxation rate by gravitational interactions is of order [2, 5]

$$\Gamma_{\rm g} \sim 4\pi G\ n\ m^2\ l^2 \tag{8}$$

where $l \sim (m\delta v)^{-1}$ is their correlation length. $\Gamma_{\rm g}(t)/H(t)$ is of order $5 \cdot 10^{-7}(f/10^{12}\ \text{GeV})^{\frac{2}{3}}$ at time t_1 but grows as $ta^{-1}(t) \propto a(t)$. Thus gravitational interactions cause the axions to thermalize and form a BEC when the photon temperature is of order 500 eV $(f/10^{12}\ \text{GeV})^{\frac{1}{2}}$. Axion BEC causes the correlation length to increase until it becomes of order the horizon. The growth in the correlation length causes the thermalization to accelerate; see Eq. (8). Once l is some fraction of t, $\Gamma_g(t)/H(t) \propto a(t)^{-3}t^3$, implying that thermalization occurs on ever shorter time scales compared to the Hubble time. The next question is whether axion BEC has implications for observation.

2 Dark matter caustics

The study of the inner caustics of galactic halos [6, 7] provides a useful tool. An isolated galaxy like our own accretes the dark matter particles surrounding it. Cold collisionless particles falling in and out of a gravitational potential well necessarily form an inner caustic, i.e. a surface of high density, which may be thought of as the envelope of the particle trajectories near their closest approach to the center. The density diverges at caustics in the limit where the velocity dispersion of the dark matter particles vanishes. Because the accreted dark matter falls in and out of the galactic gravitational potential well many times, there is a set of inner caustics. In addition, there is a set of outer caustics, one for each outflow as it reaches its maximum radius before falling back in. We exploit the catastrophe structure and spatial distribution of the inner caustics of isolated disk galaxies.

The catastrophe structure of the inner caustics depends mainly on the angular momentum distribution of the infalling particles [7]. There are two contrasting cases to consider. In the first case, the angular momentum distribution is characterized by 'net overall rotation'; in the second case, by irrotational flow. The archetypical example of net overall rotation is instantaneous rigid rotation on the turnaround sphere. The turnaround sphere is defined as the locus of particles which have zero radial velocity with respect to the galactic center for the first time, their outward Hubble flow having just been arrested by the gravitational pull of the galaxy. The present turnaround radius of the Milky Way is of order 2 Mpc. Net overall rotation implies that the velocity field has a curl, $\vec{\nabla} \times \vec{v} \neq 0$. The corresponding inner caustic is a closed tube whose cross-section is a section of the elliptic umbilic (D_{-4}) catastrophe [6, 7]. We call it a 'caustic ring', or 'tricusp ring' in reference to its shape. In the case of irrotational flow, $\vec{\nabla} \times \vec{v} = 0$, the inner caustic has a tent-like structure quite distinct from a caustic ring. Both types of inner caustic are described in detail in ref.[7].

If a galactic halo has net overall rotation and its time evolution is self-similar, the radii of its caustic rings are predicted in terms of a single parameter, called $j_{\rm max}$. Self-similarity means that the entire phase space structure of the halo is time independent except for a rescaling of all distances by $R(t)$, all velocities by $R(t)/t$ and all densities by $1/t^2$ [8, 9, 10, 11]. For definiteness, $R(t)$ is taken to be the turnaround radius at time t. If the initial overdensity around which the halo forms has a power law profile

$$\frac{\delta M_i}{M_i} \propto \left(\frac{1}{M_i}\right)^{\epsilon} \quad , \tag{9}$$

where M_i and δM_i are respectively the mass and excess mass within an initial radius r_i, then its subsequent evolution is self-similar with $R(t) \propto t^{\frac{2}{3}+\frac{2}{9\epsilon}}$ [8]. In an average sense, ϵ is related to the slope of the evolved power spectrum of density perturbations on galaxy scales. The observed power spectrum implies that ϵ is in the range 0.25 to 0.35 [10]. The prediction for the caustic ring radii is ($n = 1, 2, 3, ..$) [6, 11]

$$a_n \simeq \frac{40 \text{ kpc}}{n} \left(\frac{v_{\rm rot}}{220 \text{ km/s}}\right) \left(\frac{j_{\rm max}}{0.18}\right) \tag{10}$$

where $v_{\rm rot}$ is the galactic rotation velocity. Eq.(10) is for $\epsilon = 0.3$. The a_n have a small ϵ dependence. However, the $a_n \propto 1/n$ approximate behavior holds for all ϵ in the range 0.25 and 0.35.

Observational evidence for caustic rings of dark matter with the radii predicted by Eq. (10) was found in: the statistical distribution of bumps in a set of 32 extended and well-measured galactic rotation curves, the distribution of bumps in the rotation curve of the Milky Way, the appearance of a triangular feature in the IRAS map of the Milky Way in the precise direction tangent to the nearest caustic ring, and the existence of a ring of stars at the location of the second ($n = 2$) caustic ring in the Milky Way. The observational evidence for caustic rings of dark matter was summarized in ref. [11]. The recent improved measurement [12] of the rotation curve of our nearest large neighbor, the Andromeda galaxy, provides new evidence. The new rotation curve shows three prominent bumps at radii 10 kpc, 15 kpc and 29 kpc, whose ratios accord with Eq. (10).

To reproduce the evidence for caustic rings of dark matter, the specific angular momentum distribution on the turnaround sphere must be given by

$$\vec{\ell}(\hat{n}, t) = j_{\rm max}\ \hat{n} \times (\hat{z} \times \hat{n})\ \frac{R(t)^2}{t} \tag{11}$$

where $\hat{n}$ is the unit vector pointing to a position on the turnaround sphere, $\hat{z}$ is the axis of rotation and $j_{\rm max}$ is the parameter that appears in Eq. (10). Eq. (11) states that the turnaround sphere at time t rotates with angular velocity $\vec{\omega} = \frac{j_{\rm max}}{t}\hat{z}$. Each property of the angular momentum distribution (11) maps onto an observable property of the inner caustics: net overall rotation causes the inner caustics to be rings, the value of $j_{\rm max}$ determines their overall size, and the time dependence given in Eq. (11) is responsible for $a_n \propto 1/n$. We now show that each of these three properties follows from the assumption that the infalling dark matter is a rethermalizing axion BEC.

3 Three successes

3.1 Magnitude of angular momentum

We make the standard assumption that the angular momentum of a galaxy is due to the tidal torque applied to it by nearby protogalaxies early on when density perturbations are still small and protogalaxies close to one another [13, 14]. The amount of angular momentum galaxies typically acquire by tidal torquing can be reliably estimated by numerical simulation because it does not depend on any small feature of the initial mass configuration, so that the resolution of present simulations is not an issue in this case. The dimensionless angular momentum parameter

$$\lambda \equiv \frac{L|E|^{\frac{1}{2}}}{GM^{\frac{5}{2}}} \quad , \tag{12}$$

where G is Newton's gravitational constant, L is the angular momentum of the galaxy, M its mass and E its net mechanical (kinetic plus gravitational potential) energy, was found to have median value 0.05 [15]. In the caustic ring model the magnitude of angular momentum is given by $j_{\rm max}$. The mentioned evidence for caustic rings implies that the $j_{\rm max}$-distribution is peaked at $j_{\rm max} \simeq$ 0.18. The relationship between $j_{\rm max}$ and λ is [3]

$$\lambda = \sqrt{\frac{6}{5 - 3\epsilon}}\ \frac{8}{10 + 3\epsilon}\ \frac{1}{\pi}\ j_{\rm max} \quad . \tag{13}$$

For $j_{\rm max}$ =0.18 and ϵ in the range 0.25 to 0.35, Eq. (13) implies λ =0.051. The excellent agreement between $j_{\rm max}$ and λ gives further credence to the caustic ring model. Indeed if the evidence for caustic rings were incorrectly interpreted, there would be no reason for it to produce a value of $j_{\rm max}$ consistent with λ.

3.2 Net overall rotation

Next we ask whether net overall rotation is an expected outcome of tidal torquing. The answer is clearly no if the dark matter is collisionless. Indeed, the velocity field of collisionless dark matter satisfies

$$\frac{d\vec{v}}{dt}(\vec{r},t) = \frac{\partial \vec{v}}{\partial t}(\vec{r},t) + (\vec{v}(\vec{r},t)\cdot\vec{\nabla})\vec{v}(\vec{r},t) = -\vec{\nabla}\phi(\vec{r},t) \tag{14}$$

where $\phi(\vec{r},t)$ is the gravitational potential. The initial velocity field is irrotational because the expansion of the universe caused all rotational modes to decay away. Furthermore, it is easy to show [7] that if $\vec{\nabla}\times\vec{v} = 0$ initially, then Eq. (14) implies $\vec{\nabla}\times\vec{v} = 0$ at all later times. Since net overall rotation requires $\vec{\nabla}\times\vec{v} \neq 0$, it is inconsistent with collisionless dark matter, such as WIMPs or sterile neutrinos. If WIMPs or sterile neutrinos are the dark matter, the evidence for caustic rings, including the agreement between $j_{\rm max}$ and λ obtained above, is fortuitous.

Axions are not collisionless, in the sense of Eq. (14), because they form a rethermalizing Bose-Einstein condensate [5]. This process is quantum mechanical in an essential way and not described by Eq. (14). By *rethermalizing* we mean that the thermalization rate is larger than the Hubble rate so that the axion state tracks the lowest energy available state. The compressional (scalar) modes of the axion field are unstable and grow as for ordinary CDM, except on length scales too small to be of observational interest [2]. Unlike ordinary CDM, however, the rotational (vector) modes of the axion field exchange angular momentum by gravitational interaction. Most axions condense into the state of lowest energy consistent with the total angular momentum, say $\vec{L} = L\hat{z}$, acquired by tidal torquing at a given time. To find this state we may use the WKB approximation because the angular momentum quantum numbers are very large, of order 10^{21} for a typical galaxy. The WKB approximation maps the axion wavefunction onto a flow of classical particles with the same energy and momentum densities. It is easy to show that for given total angular momentum the lowest energy is achieved when the angular motion is rigid rotation. Rigid rotation is therefore a prediction of tidal torque theory if the dark matter is axions.

3.3 Self-similarity

Because the axion BEC rethermalization rate is larger then the Hubble rate, most axions go towards the lowest energy state consistent with the total angular momentum acquired from nearby inhomogeneities by tidal torquing. The time dependence of the specific angular momentum distribution on the turnaround sphere is then predicted. Is it consistent with Eq. (11)? In particular, is the axis of rotation constant in time?

Consider a comoving sphere of radius $S(t) = Sa(t)$ centered on the protogalaxy. As before, $a(t)$ is the cosmological scale factor. S is taken to be of order but smaller than half the distance to the nearest protogalaxy of comparable size, say one third of that distance. The total torque applied to the volume V of the sphere is

$$\vec{\tau}(t) = \int_{V(t)} d^3r\ \delta\rho(\vec{r},t)\ \vec{r}\times(-\vec{\nabla}\phi(\vec{r},t)) \tag{15}$$

where $\delta\rho(\vec{r},t) = \rho(\vec{r},t) - \rho_0(t)$ is the density perturbation. $\rho_0(t)$ is the unperturbed density. In the linear regime of evolution of density perturbations, the gravitational potential does not depend on time when expressed in terms of comoving coordinates, i.e. $\phi(\vec{r} = a(t)\vec{x}, t) = \phi(\vec{x})$. Moreover

$\delta(\vec{r},t) \equiv \frac{\delta\rho(\vec{r},t)}{\rho_0(t)}$ has the form $\delta(\vec{r}=a(t)\vec{x},t) = a(t)\delta(\vec{x})$. Hence

$$\vec{\tau}(t) = \rho_0(t)a(t)^4 \int_V d^3x\ \delta(\vec{x})\ \vec{x} \times (-\vec{\nabla}_x \phi(\vec{x})) \quad . \tag{16}$$

Eq. (16) shows that the direction of the torque is time independent. Hence the rotation axis is time independent, as in the caustic ring model. Furthermore, since $\rho_0(t) \propto a(t)^{-3}$, $\tau(t) \propto a(t) \propto t^{\frac{2}{3}}$ and hence $\ell(t) \propto L(t) \propto t^{\frac{5}{3}}$. Since $R(t) \propto t^{\frac{2}{3}+\frac{2}{9\epsilon}}$, tidal torque theory predicts the time dependence of Eq. (11) provided $\epsilon = 0.33$. This value of ϵ is in the range, $0.25 < \epsilon < 0.35$, predicted by the evolved spectrum of density perturbatuions and supported by the evidence for caustic rings. So the time dependence of the angular momentum distribution on the turnaround sphere is also consistent with the caustic ring model.

In conclusion, the phase space structure of galactic halos predicted by tidal torque theory, if the dark matter is axions, is precisely and in all respects that of the caustic ring model proposed earlier on the basis of observations. The other dark matter candidates predict a different, more chaotic phase space structure for galactic halos. Although the QCD axion is best motivated, a broader class of axion-like particles behaves in the manner described here.

References

[1] For a recent review, see *Particle Dark Matter*, edited by Gianfranco Bertone, Cambridge University Press 2010.

[2] P. Sikivie and Q. Yang, Phys. Rev. Lett. 103 (2009) 111301.

[3] P. Sikivie, Phys. Lett. B695 (2011) 22.

[4] J. Preskill, M. Wise and F. Wilczek, Phys. Lett. B120 (1983) 127; L. Abbott and P. Sikivie, Phys. Lett. B120 (1983) 133; M. Dine and W. Fischler, Phys. Lett. B120 (1983) 137.

[5] O. Erken, P. Sikivie, H. Tam and Q. Yang, Phys. Rev. D85 (2012) 063520.

[6] P. Sikivie, Phys. Lett. B432 (1998) 139; Phys. Rev. D60 (1999) 063501.

[7] A. Natarajan and P. Sikivie, Phys. Rev. D73 (2006) 023510.

[8] J.A. Fillmore and P. Goldreich, Ap. J. 281 (1984) 1.

[9] E. Bertschinger, Ap. J. Suppl. 58 (1985) 39.

[10] P. Sikivie, I. Tkachev and Y. Wang, Phys. Rev. Lett. 75 (1995) 2911; Phys. Rev. D56 (1997) 1863.

[11] L.D. Duffy and P. Sikivie, Phys. Rev. D78 (2008) 063508.

[12] L. Chemin, C. Carignan and T. Foster, Ap. J. 705 (2009) 1395.

[13] G. Stromberg, Ap. J. 79 (1934) 460; F. Hoyle, in *Problems of Cosmical Aerodynamics*, ed. by J.M. Burgers and H.C. van de Hulst, 1949, p195. Dayton, Ohio: Central Air Documents Office.

[14] P.J.E. Peebles, Ap. J. 155 (1969) 2, and Astron. Ap. 11 (1971) 377.

[15] G. Efstathiou and B.J.T. Jones, MNRAS 186 (1979) 133; J. Barnes and G. Efstathiou, Ap. J. 319 (1987) 575; B. Cervantes-Sodi et al., Rev. Mex. AA. 34 (2008) 87.

Charles B. Thorn: research narrative

Here is a brief summary of the content of the publications listed below. Papers 1,3,4, and 9 develop techniques for doing string amplitude calculations on the Giles-Thorn lightcone lattice. Paper 9 proposes that on the lattice each Neveu-Schwarz field of the superstring be replaced by an Ising model, and explains how the necessary stringy properties can be realized. Papers 1 and 4 give self energy calculations on the lightcone lattice and analyze the continuum limits to show how the known answers emerge. Paper 3 reports an interesting representation of the worldsheet propagator on the lattice. This representation is very close to the continuum analogs. It was essential to the successful continuum analysis of the Open string self energy given by Papthanasiou and me in paper 1. Paper 5 showed how to calculate determinants of Laplacian's on the worldsheet. Particularly interesting was the derivation of the known continuum expressions given by M. Kac and McKean and Singer, from their concrete definintions on a lattice. Papers 6 and 2 give new developments related to the Goddard-Thorn No ghost theorems and their proofs. Paper 7, in collaboration with my student Rojas, calculates the open string leading Regge trajectory to one loop order. As an interesting result we were able to illuminate how the zero slope limit of the one loop correction to the string Regge trajectory goes over to the known perturbative Regge trajectory in nonabelian gauge theory. Finally, paper 8 resolves some open issues associated with infrared divergences in lightcone gauge calculations in nonabelian gauge theory.

Publications During Grant Period: 1 July 2010-30 June 2013

1. Open String Self-energy on the Lightcone Worldsheet Lattice Georgios Papathanasiou, Charles B. Thorn, Phys.Rev. D88 (2013) 026014, e-Print: arXiv:1305.5850 [hep-th]

2. Null Physical States in String Models, Charles B. Thorn, JHEP 1302 (2013) 030, e-Print: arXiv:1212.4429 [hep-th]

3. Worldsheet Propagator on the Lightcone Worldsheet Lattice, Georgios Papathanasiou, Charles B. Thorn, Published in Phys.Rev. D87 (2013) 066005, e-Print: arXiv:1212.2900 [hep-th]

4. Closed String Self-energy on the Lightcone Worldsheet Lattice. Georgios Papathanasiou, Charles B. Thorn, Phys.Rev. D86 (2012) 066002, e-Print: arXiv:1206.5554

5. Determinants for the Lightcone Worldsheet. Charles B. Thorn, Phys.Rev. D86 (2012) 066010 e-Print: arXiv:1205.5815

6. Improved Proof of the No-ghost Theorem for Fermion States of the Superstring. Charles B. Thorn, Nuclear Physics B 864 (2012) 285-295. e-Print: arXiv:1110.5510

7. The Open String Regge Trajectory and Its Field Theory Limit. Francisco Rojas and Charles B. Thorn, Phys.Rev. D84 (2011) 026006 e-Print: arXiv:1105.3967

8. Resolution of Infrared Divergences in Gluon-Gluon Scattering Regulated on a Lightcone Worldsheet Lattice. Charles B. Thorn, Phys.Rev. D82 (2010) 125021 e-Print: arXiv:1010.5998

9. Digitizing the Neveu-Schwarz Model on the Lightcone Worldsheet. Charles B. Thorn, Phys.Rev. D82 (2010) 065009 e-Print: arXiv:1005.2924.

Talks and Seminars

Rick Field and students:

1. The Underlying Event at 7 TeV and 900 GeV, invited talk presented by M. Zakaria at the Berkeley-MIT LHC Workshop, MIT, Boston, MA, August 11, 2010.
2. CMS PYTHIA Tune Z1, talk presented by R. Field at the CMS General Weekly Meeting, CERN, August 18, 2010.
3. What We Have Learned About the Underlying Event From LHC Data: Findings and Surprises, talk presented by R. Field at the Hadron Collider Physics Symposium 2010 (HCP2010), University of Toronto, August 23, 2010.
4. The Transverse Multiplicity Distribution, talk presented by R. Field at the CMS Jamboree, CERN, September 1, 2010.
5. Tune Z1 New CMS PYTHIA 6.4 Tune, talk presented by R. Field at the CMS Jamboree, CERN, September 2, 2010.
6. Tune Z1 New CMS PYTHIA 6.4 Tune, talk presented by R. Field at the internal CMS LowPT-QCD Group Meeting, CERN, September 3, 2010.
7. CMS UE Data and the New Tune Z1, talk presented by R. Field at the Minimum Bias and Underlying Event Working Group Meeting, LHC Physics Centre at CERN, September 7, 2010.
8. Soft QCD at the LHC: Findings & Surprises, first talk presented by R. Field at the International Symposium on Multiparticle Dynamics (ISMD2010), Antwerp, Belgium, September 21, 2010.
9. The Quest to Find New Physics, second talk presented by R. Field at the International Symposium on Multiparticle Dynamics (ISMD2010), Antwerp, Belgium, September 25, 2010.
10. LHC UE & MB MC Tunes, talk presented by R. Field at the "ECT* - QCD at the LHC" Workshop, Trento, Italy, September 28, 2010.
11. Early LHC Data - Findings & Surprises, invited talk presented by R. Field at SESAPS Meeting, Baton Rouge, LA, October 23, 2010.
12. The Standard Model & Beyond, lecture presented by R. Field at the Introduction to Modern Physics Class, University of Florida, Gainesville, FL, November 10, 2010.
13. QCD at the LHC - Findings & Surprises, seminar presented by R. Field at the Institute for Fundamental Physics, University of Florida, Gainesville, FL, November 19, 2010.
14. Review of Tevatron MB and UE Results, talk presented by R. Field at MPI@LHC 2010, Glasgow, Scotland, November 30, 2010.
15. New LHC Tunes: What we have learned, talk presented by R. Field at MPI@LHC 2010, Glasgow, Scotland, December 3, 2010.

16. Monte-Carlo Models Facing Real Data, invited talk presented by R. Field at the Conference on LHC First Data, University of Michigan, Ann Arbor, MI, December 12, 2010.

17. Min-Bias and the Underlying Event at the LHC - Part 1, talk presented by R. Field at the Young Experimenters and Theorists Institute (YETI 2011), IPPP-Durham, Durham, England, January 10, 2011.

18. Min-Bias and the Underlying Event at the LHC - Part 2, talk presented by R. Field at the Young Experimenters and Theorists Institute (YETI 2011), IPPP-Durham, Durham, England, January 12, 2011.

19. LPCC MB&UE Working Group Common Plots, talk presented by R. Field at the internal CMS LowPT-QCD Group Meeting, CERN, February 4, 2011.

20. Strangeness and Baryon Production in Min-Bias and the Underlying Event, talk presented by R. Field at the Minimum Bias and Underlying Event Working Group Meeting, LHC Physics Centre at CERN, February 7, 2011.

21. UE Update: Lessons Learned & What's Next, talk presented by R. Field at the Minimum Bias and Underlying Event Working Group Meeting, LHC Physics Centre at CERN, February 8, 2011.

22. LPCC MB&UE Working Group Common Plots, talk presented by R. Field at the internal CMS General Weekly Meeting, CERN, February 9, 2011.

23. LPCC MB&UE Working Group Tuning Issues, talk presented by R. Field at the internal CMS Generators Group Meeting, CERN, February 14, 2011.

24. The Underlying Event at the LHC, talk presented by R. Field at the Northwest Terascale Workshop: Modeling Min-Bias and the Underlying Event, University of Oregon, Eugene, Oregon, March 7, 2011.

25. Min-Bias Collisions at the LHC, talk presented by R. Field at the Northwest Terascale Workshop: Modeling Min-Bias and the Underlying Event, University of Oregon, Eugene, Oregon, March 8, 2011.

26. Measurement of the Underlying Event Activity in Proton-Proton Collisions at 900 GeV and 7 TeV, talk presented by M. Zakaria at the American Physical Society APS April Meeting, Anaheim, California, April 30, 2011.

27. The Underlying Event & Fragmentation Tuning, talk presented by R. Field at Boost 2011, Princeton, NJ, May 23, 2011.

28. Min-Bias and the Underlying Event at the LHC (Part 1), first lecture presented by R. Field at the 51st Cracow School of Theoretical Physics, The Soft Side of the LHC, Zakopane, Poland, June 12, 2011.

29. Min-Bias and the Underlying Event at the LHC (Part 2), second lecture presented by R. Field at the 51st Cracow School of Theoretical Physics, The Soft Side of the LHC, Zakopane, Poland, June 13, 2011.

30. Common Plots and UE Comparisons, first talk presented by R. Field at the Minimum Bias and Underlying Event Working Group Meeting, LHC Physics Centre at CERN, June 17, 2011.

31. Some PYTHIA LHC Tunes, second talk presented by R. Field at the Minimum Bias and Underlying Event Working Group Meeting, LHC Physics Centre at CERN, June 17, 2011.

32. How Universal are the QCD Monte-Carlo Model Tunes?, talk presented by R. Field at the QCD at the LHC 2011 Workshop, University of St. Andrews, Scotland, August 22, 2011.

33. CMS QCD Monte-Carlo Model Tuning Efforts, talk presented by R. Field at the QCD at the LHC 2011 Workshop, University of St. Andrews, Scotland, August 25, 2011.

34. Min-Bias and the Underlying Event at the LHC, talk presented by R. Field at Physics in Collisions 2011, Vancouver, British Columbia, August 29, 2011.

35. Physics of the Underlying Event), talk presented by R. Field at the Galileo Galilei Institute for Theoretical Physics, High Energy QCD after the start of the LHC, Florence, Italy, September 14, 2011.

36. The Energy Dependence of the Underlying Event, talk presented by R. Field at the CDF-QCD Workshop, Fermilab, September 28, 2011.

37. The Underlying Event in Hadronic Collisions, talk presented by R. Field at MPI@LHC 2011, DESY, Hamburg, November 21, 2011.

38. The Energy Dependence of the Underlying Event, talk presented by R. Field at the University of Virginia, Charlottesville, VA, April 10, 2012.

39. How Universal are the QCD MC Model Tunes?, talk presented by R. Field at The Next Stretch of the Higgs Magnificent Mile, Northwestern University, Chicago, IL, May 16, 2012.

40. Are the QCD MC Models Ready for High Luminosity?, talk presented by R. Field at Perspectives on Physics and on CMS at Very High Luminosity, Alushta, Crimea, Ukraine, May 29, 2012.

41. The Energy Dependence of the Underlying Event in Hadronic Collisions, talk presented by R. Field at the 36th International Conference on High Energy Physics (ICHEP 2012), Melbourne, Australia, July 5, 2012.

42. The Energy Dependence of the Underlying Event in Hadronic Collisions, talk presented by R. Field at the QCD@LHC 2012 Workshop, Michigan State University, East Lansing, MI, August 23, 2012.

43. The Energy Dependence of the Underlying Event in Hadronic Collisions, talk presented by R. Field at the MPI@TAU Workshop, Tel Aviv University, Tel Aviv, Israel, October 15, 2012.

44. New MB & UE Data and Tunes, talk presented by R. Field at the ATLAS/CMS/LHC Monte-Carlo Workshop, LPCC, CERN, Novmber 21, 2012.

45. New MB & UE Common Plots, talk presented by R. Field at the MPI@LHC 2012 Workshop, LPCC, CERN, December 4, 2012.

46. The Energy Dependence of the Underlying Event in Hadronic Collisions, talk presented by R. Field at the QCD at Cosmic Energies Workshop, LPTHE, Paris, France, May 15, 2013.

47. Toward an Understanding of Hadron-Hadron Collisions: From Feynman-Field to the LHC, seminar presented by R. Field at the University of Antwerp, Antwerp, Belgium, May 28, 2013.

Konstantin Matchev

1. *"Mass Measurements in Missing Energy Event Topologies"*, seminar, University of Zurich, Zurich, Switzerland, July 15, 2010.
2. *"SUSY Mass Measurements at the LHC"*, invited plenary talk, SUSY 2010 conference, Bonn, Germany, August 24, 2010.
3. *"BSM Theory"*, invited plenary talk, Hadron Collider Physics Symposium, Toronto, Canada, August 26, 2010.
4. *"A Storm in a 'T' Cup (pedagogical introduction to invariant mass variables from Floxbridge and elsewhere)"*, Greater Chicagoland Seminar, Northwestern University, Evanston IL, May 20, 2011.
5. *"A Storm in a 'T' Cup (pedagogical introduction to invariant mass variables from Floxbridge and elsewhere)"*, INFN Seminar, Frascati, Italy, July 8, 2011.
6. *"Beyond the Standard Model (theory)"*, invited plenary talk, Meeting of the Division of Particles and Fields of the American Physical Society, Brown University, Providence RI, August 9, 2011.
7. *"BSM Physics with 30 fb^{-1}"*, invited plenary talk, CMS Physics Week, Brussels, Belgium, September 14, 2011.
8. *"Looking for SUSY under the LHC lamppost"*, invited plenary talk at the "Interpreting LHC Discoveries workshop", GGI, Florence, Italy, November 10, 2011.
9. *"Computer Tutorials"*, Sixth MC4BSM workshop, Cornell University, Ithaca NY, March 22, 2012.
10. *"Theory: direct EWKino"*, invited plenary talk at the LHC Physics Workshop, Chicago, May 4, 2012.
11. *"Thoughts on staus"*, invited talk at the CMS SUSY 3rd generation working group meeting, May 11, 2012.
12. *"What we are missing and what we should do about it"*, invited plenary talk at the CMS SUSY workshop, DESY, Hamburg, Germany, June 4, 2012.
13. *"The LHC and New Physics Beyond the Standard Model"*, invited plenary talk at the SESAPS 2012 Meeting, Tallahassee, November 16 2012.
14. *"Introduction to CF4"*, invited talk, Cosmic Frontier Workshop, SLAC, March 6 2013.
15. *"Complementarity Document Discussion"*, Cosmic Frontier Workshop, SLAC, March 6 2013.
16. *"CF4 Summary"*, plenary summary, Cosmic Frontier Workshop, SLAC, March 8 2013.

Pierre Ramond

1. In 2012, I was chair of DPF and gave several talks at HEPAP

2. ”The Physics Before Us”, Opening Talk of the Community Planning Meeting towards Snowmass, October 2012
3. ”Snowmass Status Report”, LCWS12 Meeting, UT Arlington, October 2012
4. TASI Lectures, June 2011
5. Lectures at Saalburg, Germany, September 2012
6. public lecture at Nova University, Ft Lauderdale, December 2010
7. public lecture at University of Colorado, Boulder June 2011
8. public lecture at Busan University, South Korea, September 2011
9. public lecture at UCF, Orlando, FL, April 2012
10. colloquium at University of Kansas, March 2013
11. plenary talk at Pheno2013, Univ. of Pittsburgh, May 2013.
12. plenary talk at ISOUPS, Asilomar, CA, May 2013.
13. seminar at StringVac2011, Busan, South Korea, September 2011
14. seminar at Miami2011, FtLauderdale, December 2011
15. seminar at CEC, Valdivia, Chile, January 2012

Pierre Sikivie

1. ”Bose-Einstein Condensation of Dark Matter Axions”, invited talk at IDM2010, the 8th International Workshop on the Identification of Dark Matter, Montpellier, France, July 29, 2010.
2. ”Bose-Einstein Condensation of Dark Matter Axions”, invited talk at the Cosmo/COS-Pa International Conference in Tokyo, September 29, 2010.
3. ”The Dark Matter Puzzle”, colloquium in the Physics Department, University of Tokyo, October 1, 2010.
4. ”Bose-Einstein Condensation of Dark Matter Axions”, video lecture at the Virtual Institute of Astroparticle Physics (VIA), October 15, 2010.
5. ”Bose-Einstein Condensation of Dark Matter Axions”, colloquium in the Physics Department of SUNY Buffalo, February 17, 2011.
6. ”Bose-Einstein Codensation of Cold Dark Matter Axions”, Physics Department colloquium at the U of Florida, Gainesville, March 31.
7. ”Bose-Einstein Condensation of Dark Matter Axions”, at the ASK 2011 International Workshop in Seoul, Korea, April 11-12. 2011.
8. ”Bose-Einstein Condensation of Dark Matter Axions” at the 7th Patras Workshop on Axions, WIMPs and WISPs, Mykonos Island, Greece, July 26-31, 2011.

9. ”Axions as Dark Matter” at the DMUTH11 Workshop on Dark Matter at CERN. Geneva, Switzerland, July 18-29, 2011.

10. ”Axion Theory Overview” at the Intensity Frontier Workshop, HSPAW Working Group, Rockville, MD, November 30 - December 2, 2011.

11. ”Bose-Einstein Condensation of Dark Matter Axions” at the Miami 2011 Topical Conference on Elementary Particles, Astrophysics, and Cosmology, Fort Lauderdale, FL, December 15-20, 2011.

12. ”Bose-Einstein Condensation of Dark Matter Axions” at the UCLA 2012 Symposium on Sources and Detection of Dark Matter and Dark Energy in the Universe, Los Angeles, CA February 22-24, 2012.

13. ”Axion Dark Matter”, Theoretical Physics seminar at the University of Kentucky, Lexington, March 5, 2012.

14. ”Dark Matter Axions”, Particle Theory seminar at the Perimeter Institute, Waterloo, Canada, March 20, 2012.

15. ”Axion BEC Dark Matter”, at the Vistas in Axion Physics Workshop, Seattle, WA April 23-26, 2012.

16. ”Dark Matter Axions”, at the 24th Rencontres de Blois on Particle Physics and Cosmology, Blois, France, May 27 - June 1, 2012.

17. ”An argument that the dark matter is axions”, Astroparticle seminar at McGill University, Montreal, Canada, October 3, 2012.

18. ”Axion Dark Matter”, Physics Department Colloquium, U of Pittsburgh, November 20, 2012.

19. ”An argument that the dark matter is axions”, Theoretical Particle Physics seminar, Yale University, January 29, 2013.

20. ”Axion Dark Matter”, Physics and Astronomy Department Colloquium, Rensselaer Polytechnic Institute, Troy, NY, January 30, 2013.

21. ”An argument that the dark matter is axions”, invited talk at the SLAC Cosmic Frontier Workshop, March 6-8, 2013.

22. ”Bose-Einstein condensation of axion dark matter”, invited talk at the Universal Themes of Bose-Einstein Condensation Workshop at the Lorentz Center of the U of Leyden, The Netherlands, March 11-15, 2013.

23. ”An argument that the dark matter is axions”, invited talk at the KITP Conference on Identifying and Characterizing Dark Matter via Multiple Probes, KITP, UC Santa Barbara, May 13-17, 2013.

24. ”Axion Cosmology”, seminar at the KITP Workshop on Hunting for Dark Matter, UC Santa Barbara, May 23, 2013.

25. ”An argument that the dark matter is axions”, invited talk at the DESY Workshop ‘Dark Matter: A Light Move’, Hamburg, Germany, June 17-19, 2013.

26. "Axions and the Galactic Angular Momentum Problem", invited talk at the 9th Patras Workshop on Axions, WIMPs and WISPs, Mainz, Germany, June 24-28, 2013.

Charles B. Thorn

1. "Resolution of IR Divergences in Gauge Theory Regulated on a Worldsheet Lattice", Invited talk to the Miami 2010 Conference, 14-19 December, Fort Lauderdale, Florida.
2. "Regge Trajectories in String and Large N Gauge Theories" talk at the 9th biennial workshop on Continuous Advances in Quantum Chromodynamics, University of Minnesota, Minneapolis, May 12 to May 15, 2011.
3. "String Self-Energy on the Lightcone Worldsheet Lattice", talk at the workshop *Scattering Amplitudes: from QCD to maximally supersymmetric Yang-Mills theory and back*, ECT Trento, Italy, 16 - 20 July 2012.

Publications

Rick Field

I am on the CDF authorship list and therefore I am listed as an author of every CDF publication. I am also on the CMS authorship list and listed as an author of every CMS publication. There have been many CDF and CDF publications over this last year. I will not list them all here. Instead I list only selected CDF and CMS publications in which a made significant contribution (i.e. one of the primary authors).

1. Early LHC Underlying Event Data - Findings and Surprises, R. Field, arXiv:1010.3558, proceedings of the Hadron Collider Physics Symposium (HCP2010), August 23-27, 2010.

2. Measurement of the Underlying Event Activity at the LHC at 7 TeV and Comparison with 0.9 TeV, The CMS Collaboration, J. High Energy Phys. 09 (2011) 109, arXiv:1107.0330.

3. Min-Bias and the Underlying Event at the LHC, R. Field, arXiv:1110.5530, proceedings of the 51st Cracow School of Theoretical Physics: The Soft Side of the LHC, Zakopane, June 11 - 19, 2011, Acta Physica Polonica B42, 2631 (2011).

4. Min-Bias and the Underlying Event at the LHC, R. Field, proceedings of Physics in Collisions (PIC2011), Vancouver, Canada, August 29, 2011, arXiv:1202.0901.

5. Measurement of Event Shapes Proton-Antiproton Collisions at 1.96 TeV, The CDF Collaboeation, Phys. Rev. D83, 112007 (2011).

6. Measurement of the Underlying Event Activity in the Drell-Yan Process in Proton-Proton Collisions at 7 TeV, The CMS Collaboration, Physics Analysis Summary, CMS-PAS-QCD-10-040, CERN, 2011.

7. The Underlying Event in Hadronic Collision, R. Field, Annual Review of Nuclear and Particle Science, 62, 427457 (2012).

R. Field - CDF and CMS Internal Notes

In large collaborations it is difficult to know who does what. For this reason I have enclosed a list of my CDF and CMS internal notes. The authors on these internal notes are the people actually doing the work. Many of my internal notes have resulted in CDF and CMS publications.

1. First Measurement of the Underlying Event Activity in Proton-Proton Collisions at 900 GeV at the LHC, D. Acosta, P. Bartalini, S. Bansal, G. Cerati, Y. Chao, D. Dobur, L. Fano, R. Field, I.K. Furic, K. Kotov, T.N. Kypreos, A. Lucaroni, D. Majumder, K. Mazumdar, L. Mucibello, M. Zakaria. CMS PAS QCD-10-001, April 2010.

2. Measurement of the Underlying Event Activity at the LHC at 7 TeV and Comparison with 0.9 TeV, P. Bartalini, S. Bansal, G. Cerati, Y. Chao, L. Fano, R. Field, A. Lucaroni, L. Mucibello, M. Zakaria, CMS PAPER QCD-10-010, June 2010.

3. The Energy Dependence of the Underlying Event in Hadronic Collisions, Rick Field, CDF/ANAL/CDF/CDFI July 2012.

4. Measurement of the Underlying Event Activity Using Leading Tracks in pp Collisions at 7 TeV, M. Zakaria, P. Bartalini, R. Field, A. Lucaroni, L. Mucibello, CMS PAS FSQ-12-020, July 2012.

Konstantin Matchev

In addition to the theory papers listed below I am also an author on the official CMS publications.

1. P. Konar, K. T. Matchev, M. Park and G. K. Sarangi, "How to look for supersymmetry under the lamppost at the LHC," Phys. Rev. Lett. **105**, 221801 (2010) [arXiv:1008.2483 [hep-ph]].

2. A. J. Barr, T. J. Khoo, P. Konar, K. Kong, C. G. Lester, K. T. Matchev and M. Park, "Guide to transverse projections and mass-constraining variables," Phys. Rev. D **84**, 095031 (2011) [arXiv:1105.2977 [hep-ph]].

3. A. Barr, T. J. Khoo, P. Konar, K. Kong, C. G. Lester, K. T. Matchev and M. Park, "A Storm in a 'T' Cup," AIP Conf. Proc. **1441**, 722 (2012) [arXiv:1108.5182 [hep-ph]].

4. J. L. Feng, K. T. Matchev and D. Sanford, "Focus Point Supersymmetry Redux," Phys. Rev. D **85**, 075007 (2012) [arXiv:1112.3021 [hep-ph]].

5. K. Matchev and R. Remington, "Updated templates for the interpretation of LHC results on supersymmetry in the context of mSUGRA," arXiv:1202.6580 [hep-ph].

6. L. Edelhauser, K. T. Matchev and M. Park, "Spin effects in the antler event topology at hadron colliders," JHEP **1211**, 006 (2012) [arXiv:1205.2054 [hep-ph]].

7. W. S. Cho, D. Kim, K. T. Matchev and M. Park, "Cracking the dark matter code at the LHC," arXiv:1206.1546 [hep-ph].

8. S. Ask, N. D. Christensen, C. Duhr, C. Grojean, S. Hoeche, K. Matchev, O. Mattelaer, S. Mrenna, A. Papaefstathiou, M. Park, M. Perelstein, and P. Skands, "From Lagrangians to Events: Computer Tutorial at the MC4BSM-2012 Workshop," arXiv:1209.0297 [hep-ph].

9. P. Avery, D. Bourilkov, M. Chen, T. Cheng, A. Drozdetskiy, J. S. Gainer, A. Korytov and K. T. Matchev *et al.*, "Precision Studies of the Higgs Golden Channel H -¿ ZZ* -¿ 4l. Part I. Kinematic discriminants from leading order matrix elements," Phys. Rev. D **87**, 055006 (2013) [arXiv:1210.0896 [hep-ph]].

10. R. Mahbubani, K. T. Matchev and M. Park, "Re-interpreting the Oxbridge stransverse mass variable MT2 in general cases," JHEP **1303**, 134 (2013) [arXiv:1212.1720 [hep-ph]].

11. J. S. Gainer, J. Lykken, K. T. Matchev, S. Mrenna and M. Park, "Spherical Parametrization of the Higgs Boson Candidate," Phys. Rev. Lett. **111**, 041801 (2013) [arXiv:1304.4936 [hep-ph]].

12. D. Bauer, J. Buckley, M. Cahill-Rowley, R. Cotta, A. Drlica-Wagner, J. Feng, S. Funk and J. Hewett *et al.*, "Dark Matter in the Coming Decade: Complementary Paths to Discovery and Beyond," arXiv:1305.1605 [hep-ph].

Pierre Ramond

1. P. Ramond, "The Five Instructions," arXiv:1201.0396 [hep-ph].

2. P. Ramond, "Group theory: A physicist's survey," Cambridge, UK: Univ. Pr. (2010) 310 p.

3. D. Belyaev, P. Hearin and P. Ramond, "The $\mathcal{OSP}(2,2|16)$ superconformal theory is free!," JHEP **1211**, 078 (2012) [arXiv:1208.1699 [hep-th]].

4. M J. Perez, P. Ramond and J. Zhang, "Mixing supersymmetry and family symmetry breakings," Phys. Rev. D **87**, no. 3, 035021 (2013) [arXiv:1209.6071 [hep-ph]].

Pierre Sikivie

1. A SQUID-based Microwave Cavity Search for Dark Matter Axions, S. Asztalos et al. (the ADMX Collaboration), Phys. Rev. Lett. 104 (2010) 041301.

2. The Emerging Case for Axion Dark Matter, Phys. Lett. B695 (2011) 22-25.

3. A Search for Scalar Chameleons with ADMX, G. Rybka et al. (the ADMX Collaboration), Phys. Rev. Lett. 105 (2010) 051801.

4. A Search for Hidden Sector Photons with ADMX, A. Wagner et al. (the ADMX Collaboration), Phys. Rev. Lett. 105 (2010) 171801.

5. Resonantly Enhanced Axion-Photon Regeneration, with G. Mueller, D.B. Tanner and K. van Bibber, in the Proceedings of the International Conference "Axions 2010", Gainesville, Florida, January 15-17, 2010, edited by David B. Tanner and Karl A. van Bibber, AIP Conf. Proc. 1274 (2010) 150-155.

6. Superconducting Radio Frequency Cavities as Axion Dark Matter Detectors, arXiv:1009.0762.

7. The Dark Matter is mostly an Axion BEC, in the Proceedings of IDM2010, the 8th International Workshop on the Identification of Dark Matter, Montpellier, France, July 26-30, 2010, PoS IDM2010:068 (2011).

8. Axion Dark Matter and Cosmological Parameters, with O. Erken, H. Tam and Q. Yang, Phys. Rev. Lett. 108 (2012) 061304.

9. A Search for Non-Virialized Axionic Dark Matter, J. Hoskins et al. (the ADMX Collaboration), Phys. Rev. D84 (2011) 121302.

10. Prospects for Searching Axion-like Particle Dark Matter with Dipole, Toroidal and Wiggler Magnets, with O.K. Baker, M. Betz, F. Caspers, J. Jaeckel, A. Lindner, A. Ringwald, Y. Semertzidis and K. Zioutas, Phys. Rev. D85 (2012) 035018.

11. Cosmic Axion Thermalization, with O. Erken, H. Tam and Q. Yang, Phys. Rev. D85 (2012) 063520 [22 pages].

12. Axion BEC Dark Matter, with O. Erken, H. Tam and Q. Yang, arXiv:1111.3976, Proceedings of the 7th Patras Workshop on Axions, WIMPs and WISPs, Mykonos, Greece, June 26 - July 1, 2011.

13. The strong CP problem, Comptes Rendus de Physique 13 (2012) 176-179.

14. The axion dark-matter eXperiment: Results and plans, with S. J. Asztalos, R. Bradley, G. Carosi, J. Clarke, C. Hagmann, J. Hoskins, M. Hotz and D. Kinion *et al.*, Proceedings of the 7th Patras Workshop on Axions, WIMPs and WISPs, Mykonos, Greece, June 26 - July 1, 2011.

15. An argument that the dark matter is axions, arXiv:1210.0040 [astro-ph.CO].

16. Axions and the Galactic Angular Momentum Distribution, with N. Banik arXiv:1307.3547 [astro-ph.GA].

Charles B. Thorn

1. C. B. Thorn, "Resolution of Infrared Divergences in Gluon-Gluon Scattering Regulated on a Lightcone Worldsheet Lattice," Phys. Rev. D **82**, 125021 (2010) [arXiv:1010.5998 [hep-th]].

2. F. Rojas and C. B. Thorn, "The Open String Regge Trajectory and Its Field Theory Limit," Phys. Rev. D **84**, 026006 (2011) [arXiv:1105.3967 [hep-th]].

3. C. B. Thorn, "Improved Proof of the No-ghost Theorem for Fermion States of the Superstring," Nucl. Phys. B **864** (2012) 285 [arXiv:1110.5510 [hep-th]].

4. C. B. Thorn, "Determinants for the Lightcone Worldsheet," Phys. Rev. D **86**, 066010 (2012) [arXiv:1205.5815 [hep-th]].

5. G. Papathanasiou and C. B. Thorn, "Closed String Self-energy on the Lightcone Worldsheet Lattice," Phys. Rev. D **86**, 066002 (2012) [arXiv:1206.5554 [hep-th]].

6. G. Papathanasiou and C. B. Thorn, "Worldsheet Propagator on the Lightcone Worldsheet Lattice," Phys. Rev. D **87**, 066005 (2013) [arXiv:1212.2900 [hep-th]].

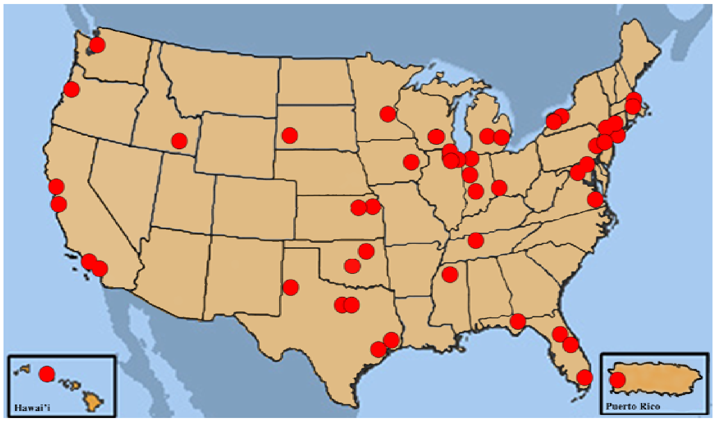
7. C. B. Thorn, "Null Physical States in String Models," JHEP **1302**, 030 (2013) [arXiv:1212.4429 [hep-th]].

8. G. Papathanasiou and C. B. Thorn, "Open String Self-energy on the Lightcone Worldsheet Lattice," Phys. Rev. D **88**, 026014 (2013) [arXiv:1305.5850 [hep-th]].

9. C. B. Thorn, "6-Vertex Model on an Open String Worldsheet," arXiv:1307.3233 [hep-th].

Task Q: QuarkNet

Overview



Since 1999, QuarkNet has provided opportunities for physicists to collaborate with local physics teachers and to interact with the students of those teachers. The teachers gain experience and appreciation of how scientists carry out research, they learn current topics and techniques in physics and they collaborate to seek ways to improve their own teaching. Approximately 550 teachers attend QuarkNet activities each summer.

Two or more physicists working at a university or laboratory may apply for consideration for their department to become a center. On acceptance of their application, the department agrees to a long-term collaboration with local teachers over topics ranging from pedagogy to recent advances in particle physics. The center recruits teachers from nearby high schools to join the collaboration. Teachers can hold long-term summer research positions or shorter workshop appointments. The teachers and physicists share the leadership for each center. The project provides support for teacher stipends, classroom equipment and teacher travel.

QuarkNet has provided nearly 400 classroom cosmic ray muon detectors (CRMDs) to teacher participants. Students use the detector to measure poperties of cosmic rays. Teachers use the device as an introduction to the practice of doing science. The students quickly come to appreciate the real nature of science, how large data sets can become and the excitement of constructing their own understanding.

QuarkNet has also collaborated to create a web-based "e-Lab." This data portal provides access to data (and analysis tools) from CMS, LIGO as well as the CRMDs. Students can create and save plots, publish posters, and markup a personal logbook. Currently more than 350 teachers have e-Lab accounts.

Activites at UF

Thomas Jordan is a member of UF's Physics Department and serves as the Project Coordinator of QuarkNet. In this role, Jordan supervises and collaborates with the project's staff.

Jordan is also responsible for the direct support of 18 of the projects 48 nodes. This support takes place in the form of conference calls, e-mails, and occasional site visits. His centers include: Boston University/Northeastern University/Brandeis University, Brookhaven Lab/Columbia University/University at Stony Brook, Florida State University, Florida Institute of Technology, Florida International University, Johns Hopkins University, Rice University/University of Houston, Rutgers University, Southern Methodist University, Syracuse University, Texas Tech University, University at Buffalo, University of Florida, University of Hawai'i, University of Maryland, University of Oregon, University of Pennsylvania, University of Rochester.

Jordan is also responsible for the summer teacher meeting at Fermilab; the so-called "Boot Camp." 25 teachers from various QuarkNet Centers attend the week-long camp. They study di-lepton triggers from CMS in several center of mass ranges. The teachers perform quality cuts on the data, reconstruct the surviving events and prepare mass plots of the suspected parent particle.

Jordan leads the Teaching and Learning Fellows–a group of five QuarkNet teachers that offer workshops that provide participants an opportunity to reflect on their teaching practice.

Furthermore, Jordan maintains the code base of analysis routines for the CRMD e-Lab. He lead the design, implementation and integration of data quality managment routines in this program year. These routines compare newly uploaded CRMD data to data recorded when the detector was behaving as expected. New data is available for public consumption if it compares favorably to existing stable data.

Since FY2010, Jordan has presented several invited and contributed talks and organized many workshops. The talks include audiences such as: The German Physical Society (March 2011), American Association of Physics Teachers (2010, 2011, 2012), Conference on Astroparticle, Particle and Space Physics, Como, Italy (2010), University of Trento, Italy (2010) American Geophysical Union (2009). Workshops include: Quito, Ecuador (April, 2013), Tbilisi, Georgia (Dec, 2012), Dubna, Russia (July 2010), Bangkok, Thailand (October 2009) and Prévessin-Moëns, France (October 2010).

FINAL REPORT

Task N — ADMX

University of Florida participation in ADMX, the Axion Dark-Matter eXperiment

D.B. Tanner, N.S. Sullivan, and P. Sikivie

Department of Physics, University of Florida, Gainesville, FL 32611

Institution: University of Florida

Street Address/City/State/Zip: 2001 Museum Road / Gainesville / FL / 32611

Principal Investigator: David B. Tanner

Postal Address: Department of Physics / University of Florida / Gainesville, FL 32611

Telephone Number: 352-392-4718

Email: tanner@phys.ufl.edu

DOE/Office of Science Program Office: Office of High Energy Physics

DOE/Office of Science Program Office Technical Contacts: Dr. Kathy Turner & Dr. Michael Salamon

DOE Grant Number: DE-FG02-97ER41029

Collaboration information: This is not collaborative proposal. The ADMX collaboration consists of individually funded groups.

Abstract

The axion is a particle that affects important issues in particle physics and astrophysics: the origin of CP symmetry in the strong interactions and the composition of the dark-matter of the universe. The present laboratory, astrophysical, and cosmological constraints suggest axions have a mass in the 1 μeV–30 meV range. Axions are especially significant as dark matter if their mass is at the low end of this range, 1–10 μeV. These dark matter axions may be detected by their coupling to photons in a tunable high-Q microwave cavity permeated by a strong external magnetic field. The University of Florida is a part of the Axion Dark-Matter eXperiment (ADMX), an experiment operated by a Washington, Berleley, Livermore, NRAO, and Florida collaboration. ADMX is the first experiment with the sensitivity possibly to observe axions as a component of the galactic halo. The collaboration has completed Phase I of an upgrade to this detector, incorporating SQUID electronics in the receiver front end and conducting a year-long data-taking run. The generation 2 experiment (Gen 2 ADMX) is a second upgrade, now underway, which will add a a high-capacity dilution refrigerator to cool the SQUID and cavity to ~100 mK. During this period, the University of Florida contributed to data analysis and to the design, specification, and acquisition of the dilution refrigerator. UF also contributed to the site preparation at the University of Washington and to research on techniques for future axion detectors.

1. INTRODUCTION

The discovery of the axion, or placing unambiguous limits on its existence, would have profound implications for two of the most important problems in contemporary physics: (i) the origin of parity P and the product of charge conjugation with parity CP symmetry in the strong interactions[1,2] and (ii) the composition of the dark matter of the universe. The most plausible mass for the axion is in the 1μeV–30 meV range. At the low end of this window axions provide the dark matter.[3–7]

The nature of dark matter is a mystery whose solution is one of the most exciting challenges in science today.[8,9] It seems probable that much of the dark matter is non-baryonic; the leading candidates are finite-mass neutrinos, weakly interacting massive particles, and axions. Only the latter two candidates could be cold dark matter, preferred in most scenarios. Between these two, the axion is special in the sense that a laboratory experiment can be carried out with current technology that can detect the particle at the expected level of abundance. Many observations imply the existence of large halos of non-luminous matter in galaxies.[10,11] ADMX searches for axions in the dark-matter halo of the galaxy.

ADMX detects axions by their stimulated conversion into microwave photons in a high Q cavity permeated by a large magnetic field. This detection method was proposed by one of us[12] and was developed during pilot experiments at Brookhaven National Laboratory[13] and at the University of Florida[14] before the construction of a large-scale experiment at Lawrence Livermore National Laboratory (LLNL).[15,16] The ADMX detector was recently moved from its initial LLNL location to the University of Washington (UW). This detector, which improved the sensitivity over the pilot detectors by at least a factor of 100, consists of a large superconducting magnet containing one or more microwave cavities. Axions in the high-field region will be stimulated to decay into microwave photons when the resonant frequency of the cavity equals the mass of the axion. Over the past few years, the detector has scanned the 1.9–3.5 μeV axion mass range; its sensitivity is such that the detector could find a signal, given the constraints on dark matter density set by astrophysical and cosmological considerations.

For several years now, ADMX has incorporated superconducting quantum interference device (SQUID) amplifiers into the front end of the receiver.[17] Their use is based on a remarkable breakthrough in making SQUIDs operate as high-gain, low-noise amplifiers into the GHz range[18] with measured SQUID noise temperatures of $T_N = 50$ mK. This noise, which is close to the quantum limit and which is far superior to the $T_N = 1.5$ K of the earlier HEMT amplifiers, requires the cavity and amplifier be cooled to 100 mK. The collaboration planned a conservative, two-step approach to this upgrade. First, in Phase I, the experiment was retrofitted to operate with SQUID amplifiers, but at the same physical temperature of $T{\sim}1.5$ K. In this case the system background noise is dominated by the physical temperature. This construction and commissioning was followed by a science run using the SQUID amplifiers prior to the move to UW. Results have been published.[19,20]

The Generation 2 Axion Dark-Matter Experiment (Gen 2 ADMX) is a second upgrade which will add a high-circulation-rate dilution refrigerator to the detector, reducing the physical temperature to $T{\sim}100$ mK. The system noise temperature is then expected to be $T_s{\sim}200$ mK. The upgrade will improve system noise performance to an extent that ADMX will be sensitive to—or be able to rule out—axions as a component of the halo of our galaxy with *all* plausible coupling strengths in the lowest decade of the allowed mass range, ($\sim$1–10 μeV).

The tasks that the University of Florida carried out during the last three years are (1) Data analysis of the science run, especially the high-resolution channel, (2) cryogenic development, including the requirements, specifications, and design of a ^{3} He refrigeratior and the dilution refrigerator for Gen 2 ADMX and also and construction of the needed 1 K pots (using pumped ^{4}He) and (3) cavity design and testing to extend the accessible axion mass range.

2. PROGRESS REPORT

2.1 Results from the ADMX science run

2.1.1 The receiver

Starting in 1995, the Axion Dark-Matter eXperiment (ADMX) collaboration has carried out a sensitive axion search.[15] This experiment has placed meaningful limits on axion couplings and densities.[21–26] Figure 1 is a schematic diagram of the axion detector during its last science run.[17,19] The magnet is a superconducting solenoid with 7.6 T central field. The cylindrical cavity (50 cm diameter, 100 cm length) is constructed of stainless steel plated with copper and subsequently annealed. The temperature of the cavity is about 1.5 K. The resonant frequency f_0 of the empty cavity is 460 MHz and its unloaded Q, including losses in the tuning rods, is ~200,000. The cavity is tuned by moving one or the other of two 8-cm-diameter tuning rods, which run the full length of the cavity, between the wall and center. Power is extracted to the low-noise receiver from the cavity coupling port. Additional coupling ports allow for transmission and reflection measurements of cavity parameters.

The first-stage preamplifiers are SQUID amplifiers. Operated at a temperature of T~1.5 K, they gave a system noise temperature of T_s~2 K. This improved the sensitivity of the detector by about a factor of two compared to the high-electron mobility transistor (HEMT) amplifiers used earlier. There is a second-stage HEMT amplifier and additional amplification at room temperature, after which the signal is converted to the 10.7 MHz intermediate frequency by an image-rejection mixer. An 8-pole crystal filter sets the 30 kHz measurement bandwidth and prevents image power from entering the second mixing stage. The signal is then mixed down a second time, in effect shifting the cavity resonant frequency to 35 kHz. A commercial FFT spectrum analyzer then generates the "medium-resolution" power spectrum, an average of 10^4 spectra at 125 Hz resolution. This resolution is well-matched to a search for the Maxwellian component of the halo, which should be about 6 channels wide. The data run using SQUID amplifiers scanned the 3.3–3.5 μeV range.[19]

The analog signal is also processed by a second "high resolution" data analysis channel. There is no averaging; instead, a commercial ADC/DSP PC board acquires and computes one 2,500,000 point, 0.04 Hz/point power spectrum. The resolution is well matched to a search for fine structure having fractional width $\sim 0(10^{-11})$ or less in the power spectrum. If any appreciable fraction of the axions are in a narrow-velocity line, it would be detected with high signal-to-noise ratio. Both analyses were carried out in parallel.

We have done a considerable amount of work on the high-resolution (HR) spectral analysis. The HR channel.[26] is an integral part of the experiment The HR data are two successive 25 s sequences of the power emitted by the cavity. The sampling rate is set by the cavity bandwidth while the resolution, set by the acquisition time, is 40 mHz. The data contain approximately 2.5 million points. A discrete axion flow produces a peak in the spectrum of microwave photons from

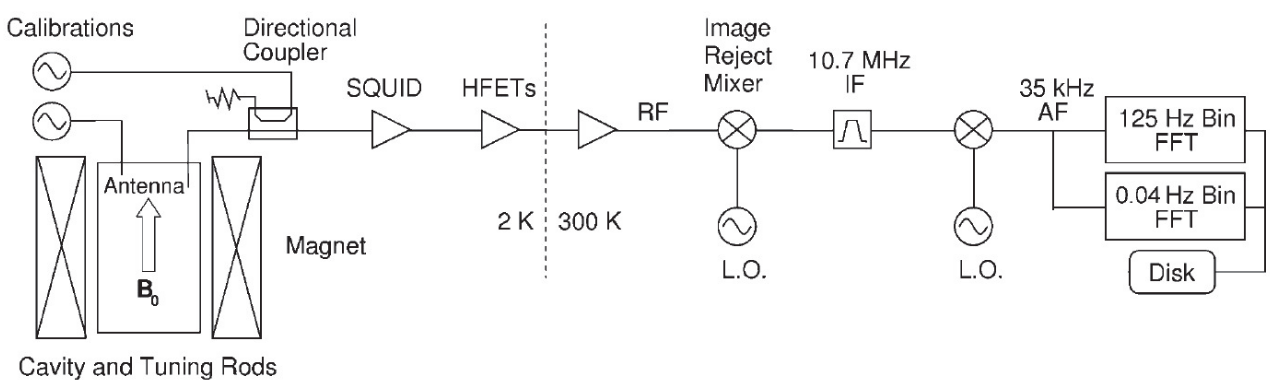
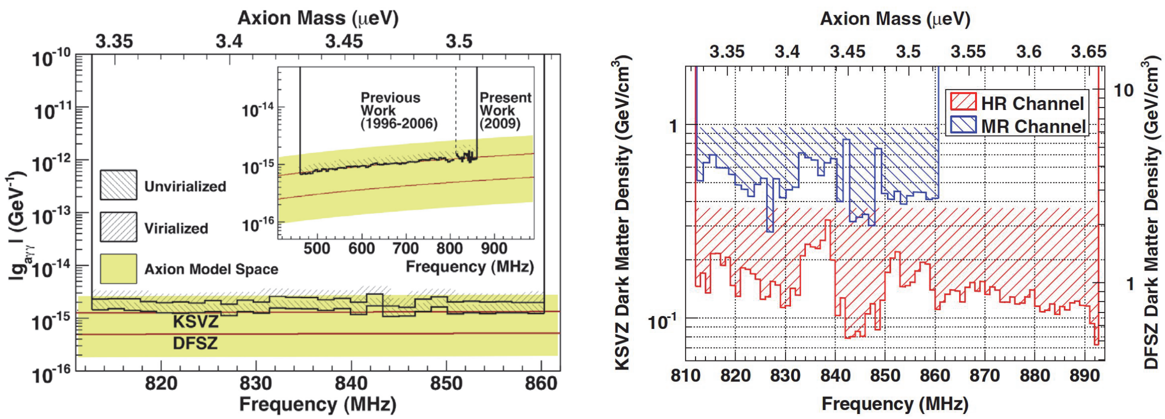


Fig. 1. Schematic diagram of the axion detector

axion conversion in our detector. In an earlier data run, the improvement in sensitivity over the medium resolution analysis was about a factor of three.[26] During the Phase I data run, Florida was responsible for the HR analysis, searching for candidate signals and monitoring the signal-to-noise achieved in the data, requiring rescans of certain frequency bands if the signal-to-noise ratio is too small, and producing the final limit plots. Results have been published[20] and further analysis is underway.

2.1.2 Exclusion limit

Figure 2 shows the axion couplings and masses excluded at the 90% confidence level by ADMX at the end of this science run.[19,20] The inset of the left panel shows the results of earlier experiments.[21–24] ADMX is the first experiment to exclude a realistic axion model: KSVZ axions of mass between 1.9 and 3.55 μeV. The plot in the right panel shows the axion-to-photon coupling $g_{a\gamma\gamma}$ as a function of the axion mass $m_a = hf/c^2$ from the high-resolution analysis. If a significant fraction of halo axions are distributed in a few narrow peaks (right panel), weaker axion two-photon couplings are excluded.[20,25,26]



(a) (b)

Fig. 2. (a) Axion couplings and masses excluded at the 90% confidence level by the experiment. The R.F. frequency range is 460–860 MHz. (b) Axion density limits for axions with velocity dispersion less than 3×10^-6c from 812 MHz to 892.8 MHz. The scale for predictions of the KSVZ and DFSZ models are shown on the left and right axes, respectively. The limit is below the KSVZ prediction. Density limits for the medium resolution channel (for axions with velocity dispersion less than $2 \times 10^{-4}c$) are also shown.

We regard the Phase I upgrade as a success. It demonstrated that SQUID amplifiers can be produced which (with proper magnetic shielding) function in the high magnetic field environment of the experiment. In addition, the amplifiers can be coupled to the axion cavity, provide adequate gain so that the system noise is the physical noise from the cavity in series with the modest noise from the amplifiers themselves, and can deliver the signal to an automated data acquisition system.

2.1.3 The high-resolution analysis

We have continued to work on the high-resolution (HR) analysis for ADMX data. The high-resolution search is designed to detect axion signals resulting from sharp features in the energy spectrum. Discrete axion flows produce peaks in the spectrum of microwave photons from axion conversion in our detector. Each peak has a daily modulation due to the Earth's rotation and an annual modulation due to orbital motion[27]. The latter causes a doppler frequency shift by ~100 Hz in the course of the year, whereas the maximum daily shift is of order 1–2 Hz. During the time (25 s) spent taking data at each cavity tune, the frequency shifts by about 2 mHz, less than the resolution. (The Doppler shift sets a practical upper limit on the HR data time duration of about

120 s. Other limits are set by the phase stability of our local oscillators and data acquisition clock. It is these latter limits that lead to the choice of 25 s measurement times.)

The HR channel was incorporated into the axion experiment because there are compelling arguments to believe that a large fraction of the local dark-matter density is in discrete low-velocity-dispersion flows.[28] The ability to look for these flows augments the discovery potential of the experiment and enriches the physics that can be done with it. Moreover, evidence has been found[29,30] in support of a particular model of these flows, called the caustic ring model of galactic halos.[31,32] When fitted to the rotation curve of our own galaxy, the model makes precise predictions for the local densities and velocity vectors of the dark matter flows in the neighborhood of the Sun.[32] The model predicts that the local dark matter is dominated by a single flow with high density and low velocity dispersion.[30]

Limits on the density of a cold flow of axion dark matter derived from our high resolution search are given in Ref. 20. The high resolution analysis has a strong potential for finding or excluding cosmic axions when a significant fraction of the local density is contained in one or few lines resulting from the incomplete thermalization of infalling dark matter.

2.2 Cryogenics research

The detailed plan of the Gen2 ADMX is to include (first) a ^{3}He refrigerator and (second) a dilution refrigerator, reducing the physical temperature to ∼400 mK and then to ∼100 mK. We expect total background (system) noise temperatures to be 50–100% higher than the physical temperature. The work that UF has done is design and risk-reduction for this low-temperature research. There are good reasons to make the intermediate step and to operate with ^{3}He. This type of refrigerator is simpler in design, easier to use, less costly, and higher in cooling capacity than a dilution refrigerator. The cryogenic environment (4.2 K reservoir, 1.7 K pumped ^{4}He pots, radiation shields, heat leaks through wiring, radiation, and gas load) will be identical to operation with a dilution refrigerator. Thus the performance of the ^{3}He system will tell us the heat load, allow us to take any necessary mitigating steps, and permit them to be tested before installing the dilution refrigerator. We have designed both the cold parts of the ^{3}He refrigerator as well as the room temperature pumping and gas-handling system. These parts are under construction.

The UF group has the lead responsibility for the design, specifications, acquisition, and (eventually) installation of the dilution refrigerator. The dilution refrigerator requirements spread to the cryogenic design of the entire insert. There is no serious issue with the amount of material to be cooled. (The MiniGrail gravitational-wave detector has much greater mass and has been cooled to ∼50 mK.[33]) The issue is keeping the heat input to the mixing chamber equal to the cooling power (∼800 μW) of the refrigerator. The sources of heat input include conduction from higher-temperature regions, thermal radiation, and mechanical vibrations. Conduction is mitigated by sinking the heat flow at each higher temperature platform (4.2 K bath, 1 K pot, and still). Careful attention to radiation shields, particularly from 300 K and 77 K regions, will reduce radiation heating to tolerable levels. With the commissioning of the ^{3}He refrigerator we will know these heat inputs much better than we do now. (Many are taken from textbook and vendor data and should be reasonably accurate. There are both known and unknown unknowns to learn about, however.)

The design of the dilution refrigerator installation in the ADMX insert is shown in Fig. 3. The refrigerator (in green) is located in the space between the 4.2 K reservoir (in blue—the outer wall and inner tube are not shown) and top of the cavity (in red). This location allows for access to the refrigerator. Other components shown include two 1.7 K pots (in red—one to condense the returning ^{3}He-^{4}He mixture and one to cool the radiation shield) pumping lines (cyan), and the top of the radiation shield (gold).

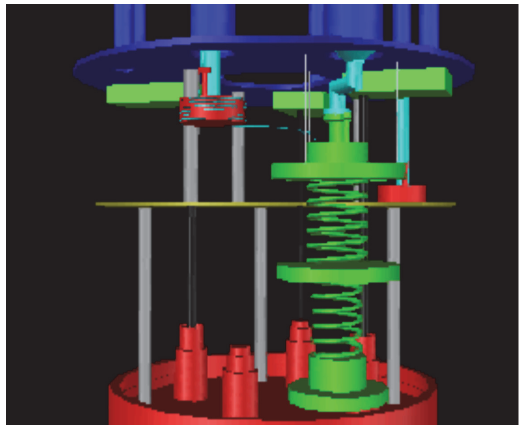


Fig. 3. Sketch of the dilution refrigerator in the axion detector. See text for a description of the components. Outer and inner cylinder walls have mostly been removed.

2.3 Commissioning and operations

Graduate students from the University of Florida ADMX group have traveled to the University of Washington to participate in the commissioning of the ADMX upgrade. They made medium-term visits (several weeks) to provide manpower for facility assembly when it was most needed. This participation increased their knowledge of the apparatus and hence their ability to carry our data analysis as the upgraded ADMX detector becomes operational.

2.4 Cavities for higher frequencies

We have carried out studies of the design and fabrication of multi-cavity arrays to allow ADMX to extend the accessible axion mass range into the GHz frequency range. We studied the properties of a half-circular cavity. This cavity has a higher resonant frequency than the circular cylinder and two such cavities could be combined in phase to make efficient use of the magnet volume while searching at higher frequencies. As discussed below, we also pursued cavities with multiple posts and partitions that also have high frequency modes with good form factors.

Challenges to reaching high frequencies are severe. The axion search rate[12,14,24] goes as $C^2_{n\ell 0}V^2Q$. Here, $C_{n\ell 0}$ is the mode-dependent form factor (0.69 for a cylinder), V is the cavity volume, and Q is the quality factor of the cavity. The TM_{010} resonant frequency of a circular cylinder is $f_{010} = 230/D$ m-MHz, with D the diameter. Hence, the volume decreases *at least* as fast as $1/f^2$. In practice, the aspect ratio (length L to diameter D) cannot get too large, as the number of TE and TEM modes becomes large and the requirements on cavity precision, so as to avoid mode localization, become severe.[34] The ADMX detector, and the Florida pilot experiment, use $L/D \approx 2$–3; keeping the aspect ratio constant makes the volume decrease as $1/f^3$.

It is possible to fill the magnet volume with a number of cylindrical cavities, design a servo to tune them to the same frequency,[35] and combine their output in phase in order to increase the signal strength. This is the approach of the 4-cavity array already tested by ADMX and this approach will work, although with increasing complexity, and seems to be able to cover the next factor of two in frequency above the tuning range of a single cylindrical cavity.

We also are studing an attractive alternative to a large number of cavities: the use of a single resonator made up of a periodic array of metallic posts or vanes in the circular cross-section of the magnet.[34] This resonator has a high-frequency TM_{010} mode whose frequency is determined by the dimensions of the unit cell and not by the total cavity dimension. If the rods are moved, the resonant frequency can be changed. Two examples of these concepts are shown in Fig. 4. In both cases half of the posts or vanes are fixed and half move, changing the resonant frequency. The paths taken by those that do move are identical, so that a single rotary mechanism can achieve the necessary motion.

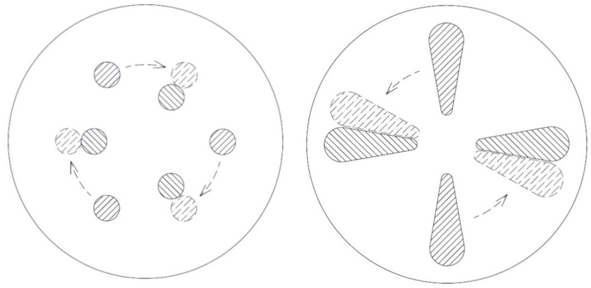


Fig. 4. schematic drawing of cavity tuning methods. The left side shows a 6-post (3 moving) resonator. The right side shows a 4-vane (2 moving) design. The arrows indicate the motion of the rotating post/vanes (rotor) from solid hatching (maximum TM_{010} frequency) to the dash hatching (minimum TM_{010} frequency).

We have modeled this concept using Comsol.[36] The simulations calculate the resonant frequency, the cavity Q, the form factor C_{nl0}, and the cavity Q as a function of the location of the rods, their number, and their size. Results for the electric field the 6-post design are shown in Fig. 5 and results for the electric field the 4-vane design is shown in Fig. 6. The simulations shown are for the two extreme positions of the moving rods. The left panels show the fields at the lowest resonance frequency and the right panels show the fields for the highest resonance frequency.

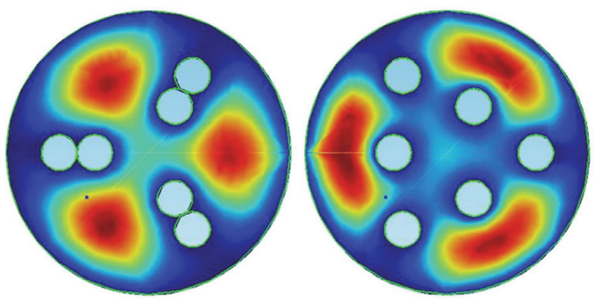


Fig. 5. TM_{010} resonant frequency z-axis electric field distribution for a 6-post cavity. The strongest electric field is dark red; the weakest is dark blue.

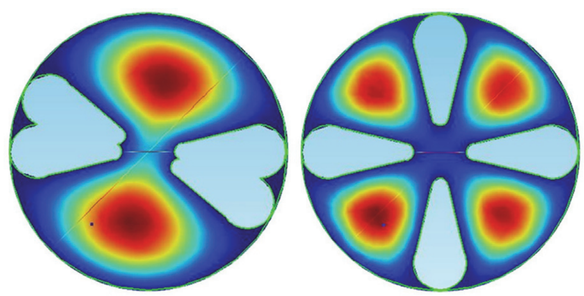


Fig. 6. TM_{010} resonant frequency z-axis electric field distribution for a 4-vane cavity.

The 6-post design would tune ADMX's cavity from 1020–1290 MHz. The 4-vane design has a somewhat larger tuning range, covering 900–1280 MHz. We have made a number of other simulations not shown here. All rely on the rotor/stator approach shown above. More elements increase the resonant frequency, roughly as $\sqrt{N}$. Both the form factor and the Q are worse than in the single cavity, but the increased volume overwhelms these degradations, and the emitted power from axion→photon conversion is 5–25 times that of a *single* cylindrical cavity operating at the same frequency. Research on these "photonic bandgap" resonators is continuing.

Appendix: Bibliography and References Cited

1. R.D. Peccei and H. Quinn, Phys. Rev. Lett. **38**, 1440 (1977) and Phys. Rev. D **16**, 1791 (1977).
2. S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978); F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).
3. L. Abbott and P. Sikivie, Phys. Lett. B**120**, 133 (1983).
4. J. Preskill, M. Wise and F. Wilczek, Phys. Lett. B **120**, 127 (1983).
5. M. Dine and W. Fischler, Phys. Lett. B **120**, 137 (1983).
6. M.S. Turner, Phys. Rep. **197**, 67 (1990); G.G. Raffelt, Phys. Rep. **198**, 1 (1990).
7. C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667**, 1 (2008).
8. S. Perlmutter G. Aldering, G. Goldhaber, R.A. Knop, P. Nugent, P.G. Castro, S. Deustua, S. Fabbro, A. Goobar, D.E. Groom, I.M. Hook, A.G. Kim, M.Y. Kim, J.C. Lee, N.J. Nunes, R. Pain, C.R. Pennypacker, R. Quimby, C. Lidman, R. S. Ellis, M. Irwin, R.G. McMahon, P. Ruiz-Lapuente, N. Walton5 B. Schaefer, B.J. Boyle, A. V. Filippenko, T. Matheson, A. S. Fruchter, N. Panagia, H.J.M. Newberg, W. J. Couch, and The Supernova Cosmology Project, Astrophys. J. **517**, 565 (1999)
9. A.G. Riess, A.V. Filippenko, P. Challis, A. Clocchiatti, A. Diercks, P.M. Garnavich, R.L. Gilliland, C.J. Hogan, S. Jha, R.P. Kirshner, B. Leibundgut, M.M. Phillips, D. Reiss, B.P. Schmidt, R.A. Schommer, R.C. Smith, J. Spyromilio, C. Stubbs, N.B. Suntzeff, and J. Tonry, Astron. J. **116**, 1009 (1998).
10. K.G. Begeman, A.H. Broeils, and R.H. Sanders, Mon. Not. R. Astron. Soc. **249**, 523–537 (1991).
11. D. Clowe M. Bradac, A.H. Gonzalez, M. Markevitch, S.W. Randall, C. Jones, and D. Zaritsky, Astrophys. J. **648**, L109 (2006).
12. P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983).
13. S. DePanfilis, A.C. Melissinos, B.E. Moskowitz, J.T. Rogers Y.K. Semertzidis, W.U. Wuensch, H.J. Halama, A.G. Prodell, W.B. Fowler and F.A. Nesrick, Phys. Rev. Lett. **59**, 839 (1987); W.U. Wuensch, S. DePanfilis-Wuensch, Y.K. Semertzidis, J.T. Rogers, A.C. Melissinos, H.J. Halama, B.E. Moskowitz, A.G. Prodell, W.B. Fowler, and F.A. Nezrick, Phys. Rev. D **40**, 3153 (1989).
14. C. Hagmann, P. Sikivie, N.S. Sullivan and D.B. Tanner, Phys. Rev. D **42**, 1297 (1990).
15. H. Peng, S. Asztalos, E.J. Daw, N.A. Golubev, C.A. Hagmann, D. Kinion, J. LaVeigne, D.M. Moltz, F.A. Nezrick, J. Powell, L.J. Rosenberg, P. Sikivie, W. Stoeffl, N.S. Sullivan, D.B. Tanner, M.S. Turner, and K. van Bibber, Nucl. Instrum. Methods A **444**, 569–583 (2000).
16. Richard Bradley, John Clarke, Darin Kinion, Leslie J Rosenberg, Karl van Bibber, Seishi Matsuki, Pierre Sikivie, Rev. Mod. Phys. **75**, 777 (2003).
17. S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L.J Rosenberg, G. Rybka, A. Wagner, J. Hoskins, C. Martin, N.S. Sullivan, D.B. Tanner, R. Bradley, and John Clarke, Nucl. Instrum. Methods A **656**, 39 (2011).
18. M. Mück, M.-O. André, J. Clarke, J. Gail and C. Heiden, Appl. Phys. Lett. **72**, 2885 (1998); Appl. Phys. Lett. **75**, 3545 (1999); 75, 698, 1999
19. S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L.J Rosenberg, G. Rybka, J. Hoskins, J. Hwang, P. Sikivie, D.B. Tanner, R. Bradley, and J. Clarke, Phys. Rev. Lett. **104**, 041301/1–4 (2010).

20. J. Hoskins, J. Hwang, C. Martin, P. Sikivie, N.S. Sullivan, D.B. Tanner, M. Hotz, L.J Rosenberg, G. Rybka, A. Wagner, S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, R. Bradley, and J. Clarke, Phys. Rev. D **84**, 121302(R)/1–5 (2011).
21. C.A. Hagmann, D. Kinion, W. Stoeffl, K. van Bibber, E.J. Daw, H. Peng, L.J. Rosenberg, J. LaVeigne, P. Sikivie, N.S. Sullivan, D.B. Tanner, F.A. Nezrick, M.S. Turner, D.M. Moltz, J. Powell, and N.A. Golubev, Phys. Rev. Lett. **80**, 2043, (1998).
22. S. Asztalos, E. Daw, H. Peng, L.J. Rosenberg, C. Hagmann, D. Kinion, W. Stoeffl, K. van Bibber, P. Sikivie, N.S. Sullivan, D.B. Tanner, F. Nezrick, M.S. Turner, D.M. Moltz, J. Powell, M.-O. André, J. Clarke, and M. Mück, Phys. Rev. D **64**, 092003-1–28 (2001).
23. S.J. Asztalos, E. Daw, H. Peng, L.J. Rosenberg, C. Hagmann, D. Kinion, W. Stoeffl, K. van Bibber, J. LaVeigne, P. Sikivie, N.S. Sullivan, D.B. Tanner, F. Nezrick, M.S. Turner, and D.M. Moltz, Astrophys. Jour. Lett. **571**, L27-L30 (2002).
24. S.J. Asztalos, R.F. Bradley, L. Duffy, C. Hagmann, D. Kinion, D.M. Moltz, L.J Rosenberg, P. Sikivie, W. Stoeffl, N.S. Sullivan, D.B. Tanner, K. van Bibber, and D.B. Yu, Phys. Rev. D **69**, 011 101(R)-1–5 (2004).
25. L. Duffy, P. Sikivie, D.B. Tanner, S. Asztalos, C. Hagmann, D. Kinion, L.J. Rosenberg, K. van Bibber, D. Yu, and R.F. Bradley, Phys. Rev. Lett. **95**, 091304 (2005).
26. L.D. Duffy, P. Sikivie, D.B. Tanner, S.J. Aszatalos, C. Hagmann, D. Kinion, L.J Rosenberg, K. van Bibber, D.B. Yu, and R.F. Bradley, Phys. Rev. D **74**, 012006 (2006).
27. F.S. Ling, P. Sikivie and S. Wick, Phys. Rev. D **70**, 123503 (2004).
28. P. Sikivie and J. Ipser, Phys. Lett. B **291**, 288 (1992).
29. W. Kinney and P. Sikivie, Phys. Rev. D **61**, 087305 (2000).
30. P. Sikivie, Phys. Lett. B **567**, 1 (2003).
31. P. Sikivie, Phys. Lett. B **432**, 139 (1998).
32. P. Sikivie in *Proceedings of the 2nd International Workshop on the Identification of Dark Matter* (World Scientific, 1999), p. 58.
33. A. de Waard, M. Bassan, Y. Benzaim, V. Fafone, J. Flokstra, G. Frossati, L. Gottardi, C.T. Herbschleb, A. Karbalai-Sadegh, K. Kuit, H. van der Mark, Y. Minenkov, J.B.R. Oonk, G.V. Pallottino, J. Pleikies, A. Rocchi, O. Usenko, and M Visco, Class. Quantum Grav. **23**, S79 (2006).
34. C. Hagmann, P. Sikivie, N.S. Sullivan and D.B. Tanner, Rev. Sci. Instrum. **6**, 1076 (1990).
35. Eric D. Black, Am. J. Phys. **69**, 79 (2001).
36. `http://www.comsol.com/`

Papers published during the funding period

1. "SQUID-based microwave cavity search for dark-matter axions," S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L.J Rosenberg, G. Rybka, J. Hoskins, J. Hwang, P. Sikivie, D.B. Tanner, R. Bradley, and J. Clarke, *Phys. Rev. Lett.* **104**, 041301/1–4 (2010).
2. "Search for chameleon scalar fields with the axion dark matter experiment," G. Rybka, M. Hotz, L.J Rosenberg, S.J. Asztalos., G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, J. Hoskins, C. Martin, P. Sikivie, D.B. Tanner, R. Bradley, and J. Clarke, *Phys. Rev. Lett.* **105**, 051801/1–4 (2010).
3. "Resonantly-enhanced axion-photon regeneration," G. Mueller, P. Sikivie, D.B. Tanner, and K. van Bibber, in *Axions 2010* edited by David B. Tanner and K. A. van Bibber (American Institute of Physics, New York, 2010), pp. 150–155.
4. "Search for hidden sector photons with the ADMX detector," A. Wagner, G. Rybka, M. Hotz, L.J Rosenberg, S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, J. Hoskins, C. Martin, P. Sikivie, D.B. Tanner, R. Bradley, and J. Clarke, *Phys. Rev. Lett.* **105**, 171801/1–4 (2010).
5. "Search for nonvirialized axionic dark matter," J. Hoskins, J. Hwang, C. Martin, P. Sikivie, N.S. Sullivan, D.B. Tanner, M. Hotz, L.J Rosenberg, G. Rybka, A. Wagner, S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, R. Bradley, and J. Clarke, *Phys. Rev. D* **84**, 121302(R)/1–5 (2011).
6. "The Axion Dark-Matter eXperiment: Results and plans," S.J. Asztalos, R. Bradley, G. Carosi, J. Clarke, C. Hagmann, J. Hoskins, M. Hotz, D. Kinion, C. Martin, L.J Rosenberg, G. Rybka, P. Sikivie, N.S. Sullivan, D.B. Tanner, K. van Bibber, and A. Wagner, in *Proceedings of the 7th Patras Workshop on Axions, WIMPs and WISPs* edited by Marc Schumann and Konstantin Zioutas (Verlag Duetsches Elektronen-Synchrotron, Hamburg, 2011), pp. 47–50. (DOI: 10.3204/DESY-PROC-2011-04/rybka_gray)
7. "Design and performance of the ADMX SQUID-based microwave receiver," S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L.J Rosenberg, G. Rybka, A. Wagner, J. Hoskins, C. Martin, N.S. Sullivan, D.B. Tanner, R. Bradley, and John Clarke, *Nucl. Instrum. Methods A* **656**, 39–44 (2011).
8. "Low-cost move of a large superconducting magnet on a trailer with air-ride suspension," B. Thomas, D. Will, J. Heilman, K. Tracy, M. Hotz, D. Lyapustin, L.J Rosenberg, G. Rybka, A. Wagner, J. Hoskins, C. Martin, N.S. Sullivan, D.B. Tanner, S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, R. Bradley, and J. Clarke, *J. Appl. Packag. Res.* **6**, 79–92 (2012).
9. "New light, weakly coupled particles," J.I. Collar, R. Essig, J.A. Jaros, A. Afanasev, O. Baker, B. Batell, J. Beacham, F. Bossi, J. Boyce, M. Buckley, G. Carosi, R. Cowan, A. Denig, B. Echenard, A. Freyberger, A. Gasparian, Y. Gershtein, M. Graham, P.W. Graham, A. Haas, J. Hartnett, I. Irastorza, J. Jaeckel, I. Jaegle, M. Lamm, A. Lindner, W.C. Louis, D. McKeen, H. Merkel, G. Mills, L.A. Moustakas, G. Mueller, M. Pivovaroff, R. Povey, S. Rajendran, J. Redondo, A. Ringwald, P. Schuster, M. Schwarz, P. Sikivie, K. Sigurdson, J. Steffen, S. Stepanyan, M. Strassler, D. Tanner, M. Tobar, N. Toro, A. Upadhye, S. Vahsen, R. Van de Water, J. Vogel, D. Walker, A. Weltman, W. Wester, N. Weiner, G. Wiedemann, B. Wojtsekhowski, and K. Zioutas, in *Fundamental Physics at the Intensity Frontier,* J.L. Hewett, H. Weerts, R. Brock, J. Butler, B. Casey, *et al.* (ANL-HEP-TR-12-25, SLAC-R-991, arXiv:1205.2671 [hep-ex], 11 May 2012).

10. "Search for Axionic Dark Matter," D.B. Tanner (for the ADMX collaboration), *Proceedings of the 9th Patras Workshop on Axions, WIMPs and WISPs* (Verlag Duetsches Elektronen-Synchrotron, Hamburg, 2013) DESY-PROC-2013-XX.
11. "Axion Dark Matter Searches," Ian P Stern for the ADMX Collaboration, to appear in *Proceeedings of the 2013 Particle Physics and Cosmology Workshop.*

Presentations given during the funding period

1. "Results from phase 1: Axion Dark-Matter eXperiment," David B. Tanner, *7th Patras Workshop on Axions, WIMPs and WISPs* (Mykonos, 27 June 2011). (Invited)
2. "Resonantly-Enhanced Axion Photon Regeneration," David B. Tanner, *Fundamental Physics at the Intensity Frontier* (Rockville, 30 November 2011). (Invited)
3. "Concepts for Microwave Cavities at Higher & Lower Frequencies," David B. Tanner, *Vistas in Axion Physics: A Roadmap for Theoretical and Experimental Axion Physics through 2025* (Seattle, 24 April 2012). (Invited)
4. "High Finesse Optical Cavities," David B. Tanner, *Vistas in Axion Physics: A Roadmap for Theoretical and Experimental Axion Physics through 2025* (Seattle, 24 April 2012). (Invited)
5. "Axion overview," David B. Tanner, *Closing in on Dark Matter* (Aspen, 1 February 2013). (Invited)
6. "Lasers and optical cavities to search for new particles," David B. Tanner, *Intensity Frontier Workshop* (Argonne, 25 April 2013). (Invited)
7. "ADMX enters its second generation," Pierre Sikivie, *9th Patras Workshop on Axions, WIMPs and WISPs* (Mainz, 25 June 2013). (Invited)
8. "Axion Dark Matter Searches," Ian P Stern, *2013 Particle Physics and Cosmology Workshop* (Deadwood, July 2013). (Invited)
9. "Searches for Structured Axion Dark Matter with ADMX," M. Hotz,* C. Boutan, D. Lyapustin, L.J Rosenberg, G. Rybka, A. Wagner, G. Carosi, S.J. Asztalos, C. Hagmann, D. Kinion, K. Van Bibber, J. Hoskins, J. Hwang, C. Martin, P. Sikivie, I. Stern, N.S. Sullivan, D.B. Tanner, J. Clarke, R. Bradley, *April Meeting of the American Physical Society*, D14.02 (Atlanta, 31 March 2012).
10. "Improvements to the Axion Dark Matter eXperiment High Resolution Axion Search," J. Hoskins,* J. Hwang, C. Martin, P. Sikivie, I. Stern, N.S. Sullivan, D.B. Tanner, C. Boutan, M. Hotz, D. Lyapustin, L.J Rosenberg, G. Rybka, A. Wagner, S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, R. Bradley, J. Clarke, *April Meeting of the American Physical Society*, D14.03 (Atlanta, 31 March 2012).
11. "ADMX Phase II: Progress and Expected Sensitivity," D. Lyapustin,* S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, J. Hoskins, J. Hwang, C. Martin, P. Sikivie, I. Stern, N.S. Sullivan, D.B. Tanner, C. Boutan, M. Hotz, L.J Rosenberg, G. Rybka, A. Wagner, R. Bradley, J. Clarke. *April Meeting of the American Physical Society*, D14.04 (Atlanta, 31 March 2012).
12. "High-Frequency Resonant Cavities for the Detection of Axion Dark Matter," I. Stern,* A.A. Chisholm, J. Hoskins, J. Hwang, C. Martin, P. Sikivie, N.S. Sullivan, D.B. Tanner, C. Boutan, M. Hotz, D. Lyapustin, G. Rybka, A. Wagner, L.J Rosenberg, S.J. Asztalos,

G. Carosi, C. Hagmann, D. Kinion, K. Van Bibber, R. Bradley, J. Clarke, *April Meeting of the American Physical Society*, D14.05 (Atlanta, 31 March 2012).

13. "Searching for Dark Matter Axions beyond ADMX Phase II," G. Carosi,* S.J. Asztalos, C. Hagmann, D. Kinion, K. van Bibber, J. Hoskins, J. Hwang, C. Martin, P. Sikivie, I. Stern, N.S. Sullivan, D.B. Tanner, C. Boutan, M. Hotz, D. Lyapustin, L.J Rosenberg, G. Rybka, A. Wagner, R. Bradley, and J. Clarke, *April Meeting of the American Physical Society*, D14.06 (Atlanta, 31 March 2012).
14. "Searching for hidden Sector Photons and Chameleons with ADMX A. Wagner,* C. Boutan, M. Hotz, D. Lyapustin, L.J Rosenberg, G. Rybka, S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, J. Hoskins, J. Hwang, C. Martin, P. Sikivie, I. Stern, N.S. Sullivan, D.B. Tanner, R. Bradley, J. Clarke, *April Meeting of the American Physical Society*, J11.06 (Atlanta, 1 April 2012).

Students supported during the funding period

Jeffrey Hoskins was supported 2010–2013. He contributed to cavity development and the major part of the high-resolution spectral analysis. He also traveled to Seattle for work on installation of the experiment at the new site. He will graduate with a PhD in December 2013.

Ian Stern was involved with the project since summer 2012. He has carried out cavity simulation computations and also worked on measurement of cavity performance. This work is continuing, with graduation expected in late 2014 or early 2015. He also traveled to Seattle for work on installation of the experiment at the new site.

Catalin Martin was partially supported by the project during 2011–2013. He worked on installing the field-canceling magnet for the SQUID region in the new insert, designing in particular new current leads to reduce liquid helium consumption. He is now Assistant Professor at Ramapo College, New Jersey.