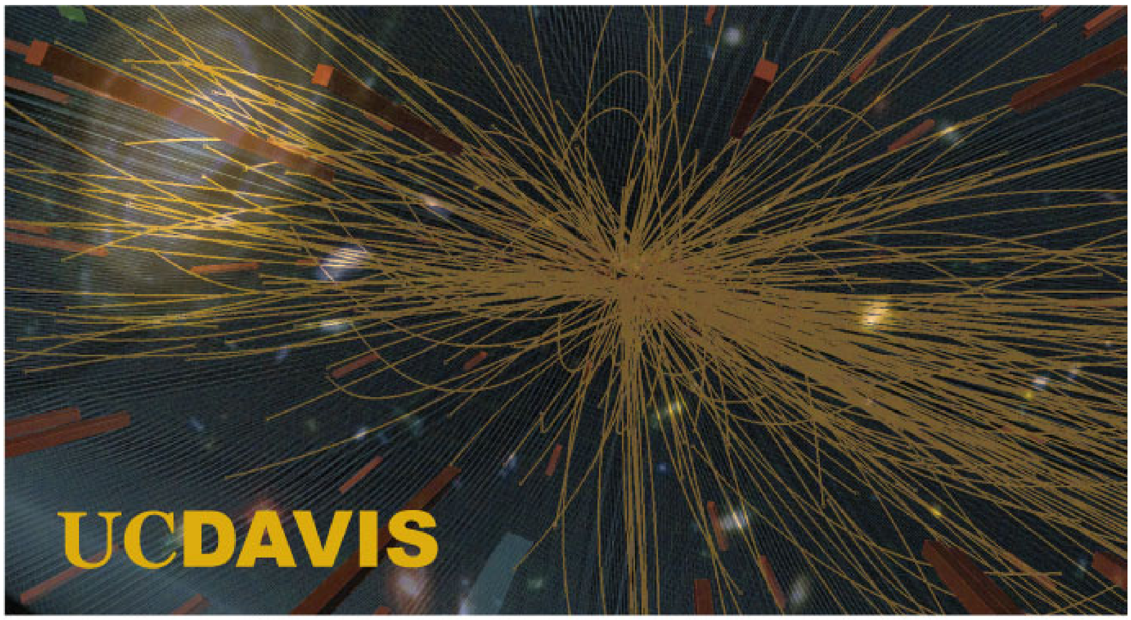
Final Report:
Research in High Energy Physics and Cosmology at the University of California, Davis



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Introduction

We describe here the research conducted in the past several years, since January 2010, at the University of California, Davis, covering the areas of experimental and theoretical particle physics and cosmology in the years 2013-2017. We believe that we are at an exceptional time for discovery in these fields, with the Large Hadron Collider delivering large numbers of proton-proton collisions at high energy, new neutrino and dark matter experiments coming on line soon, and ambitious projects such as the LSST under construction. The answers to the questions we ask here will profoundly alter our understanding of the universe. If history is any guide, a deeper understanding of the workings of matter, energy, space, and time will lead to new technologies and industries, and, of course, ever-deeper questions.

Over the past two decades UC Davis has worked to renew and expand the number and quality of the faculty members working in these areas. The experimental high energy program is thriving and vibrant, with six faculty members and two active emeriti. We have recently recruited a junior faculty member in experimental collider physics and the department's next priority is to recruit a faculty member in the area of experimental neutrino/dark matter physics. The theoretical particle phenomenology group is regarded as one of the strongest such groups in the world, with one senior member and four mid-career members leading the effort. In cosmology we have two internationally recognized leaders in the fields spanning quantum gravity, inflationary cosmology, and particle cosmology.

There is a very lively intellectual atmosphere within the department, with regular cross-disciplinary seminars and events. We organize numerous workshops at Davis which cross the boundaries between all of the subfields, and bring in experts from around the world. This "cosmic convergence" at Davis truly unites us in our scientific goals and serves as very fertile ground in which new ideas can grow.

We have organized our work, and our report, into several tasks, which align with the Office of High Energy Physics program areas as follows:

Task	Research Areas	OHEP Program
A	Experimental Collider Physics	Energy Frontier
B1	Particle Phenomenology/Quantum Gravity	Theoretical Physics
B2	Theoretical Cosmology	Theoretical Physics
C	Experimental Neutrino Physics	Intensity Frontier
L	Direct Dark Matter Detection	Cosmic Frontier
D	Particle Detector Development	Advanced Detector Development

In reading this report we ask you to keep in mind the thing we, as a group, value most: new ideas. Only with truly novel approaches to the questions facing us will we make the discoveries that await. This report highlights the new ideas that we have generated in the recent past, which have helped us push the boundaries of our science, and points the way to a future for our group rich with the sort of new ideas we have demonstrated.

1 Task A: Experimental Collider Physics

1.1 Introduction

The Large Hadron Collider at CERN recently completed its second full year of high-intensity operation, at a proton-proton center of mass energy of 8 TeV. The CMS experiment (Compact Muon Solenoid), under development and construction for more than two decades, has ammassed large amounts of collision data, and is producing analysis results and papers at a very high rate. There are 25 fb^{-1} of integrated luminosity available for analysis. Last July 2012 saw the dramatic announcement of the discovery of a new boson with properties compatible with that of the standard model Higgs boson. The era of discovery at the LHC has finally arrived!

The experimental particle physics group at UC Davis has been a member of US CMS since its inception in the early 1990s, and a member of the CDF collaboration for over a decade. The group now comprises six faculty, two active emeriti, three senior researchers, four postdocs, and ten graduate students. With the end of the Tevatron era and the LHC era well underway, the group's objectives for this research are straightforward:

- Continue to participate vigorously in the ongoing analysis of the 2011 and 2012 CMS data samples, mainly focusing on new particle searches including those for the Higgs boson, supersymmetry, new heavy quarks, new bosons or other new resonances, and dark matter.
- Continue to contribute to the operation, maintenance, calibration, and future upgrades of the CMS detector hardware and software.

The project report below will fully expand upon the recent accomplishments of the group in CMS and CDF in the last several years.

1.2 Task A Personnel

Faculty Members

The faculty members in the UC Davis CMS group are:

- **Prof. John Conway**, who works on the CMS forward pixel project and in the search for the Higgs boson, new heavy quarks, and long-lived heavy particles. Conway serves on the CMS Statistics Committee and the Exotica Publications Committee, and co-convenes the CMS Higgs to Tau subgroup.
- **Prof. Maxwell Chertok**, who works on the CMS forward pixel project, and in the search for supersymmetry and exotic Higgs boson signatures. Chertok has completed a stint on the FNAL LPC Management board.
- **Prof. Robin Erbacher**, who works on the endcap muon CSC system, co-convenes the CMS B2G (Beyond the 2nd Generation) Physics Group's 4th generation and vector quark subgroup ("XTY"), and leads the UC Davis group's effort in searches for heavy resonances or new physics with top quark-like signatures. Erbacher serves on HEPAP (2012-14) and co-convenes the Snowmass 2013 Top Quark study group within the High Energy Frontier group.
- **Prof. S. Mani Tripathi**, who has worked for many years in the EMU system, developing electronics (including for the ME1/1 upgrade) and leads a group in the search for new physics with high energy photons.

- **Prof. Michael Mulhearn**, who joined the Davis group in 2011, and works on the Level 1 calorimeter trigger upgrade, studies of the Higgs boson, and exotic searches for magnetic monopoles.

Senior Researchers

The UC Davis group has three senior researchers, each of whom we partially supported under the award. These group members bring deep expertise and experience to the project, along with which comes continuity in the group's activities and responsibilities. They serve an extremely important role in the education and training of the postdoctoral researchers and graduate students in the group:

- **Dr. Peter Timothy Cox**, resident at CERN, serves as the deputy Level 2 manager of the EMU CSC system, a major US responsibility. He is also the leader of the endcap muon reconstruction software project.
- **Dr. John Smith**, an expert in modern Monte Carlo programs, statistical data analysis, and tracking software, contributes to the Higgs boson searches and to our search for heavy unstable charged particles.
- **Dr. Richard Breedon**, with two decades of experience with the CMS EMU system, has significant responsibilities in the ME1/1 and ME4/2 upgrade projects. He is Chair of the Muon Editorial Board and is a member of the CMS Publications Committee's language editor pool.

Postdoctoral Researchers

The Davis group presently has five postdoctoral researchers, all based full time at CERN:

- **Dr. Sushil Chauhan** plays an important role in the monitoring of the proton-proton collision region ("beam spot") location. This is crucial for numerous physics analyses. He is a leading member of the group searching for new physics with photons with Prof. Tripathi.
- **Dr. Justin Pilot**, who started with the UC Davis group in 2012, is working with Prof. Erbacher on the search for new physics in the top quark sample, and on the operations and monitoring of the performance of the CSCs. Pilot has become a CMS expert on jet substructure and boosted top, and is leading a group study intiated in BOOST 2012. He is also the B2G Physics Group liaison to the CMS Jet/MET group.
- **Dr. Rachel Yohay**, a new member of the Davis group in 2012, is developing new algorithms for reconstructing exotic pseudoscalar Higgs boson decays, and contributing to the forward pixel project, under the leadership of Prof. Chertok.
- **Dr. Scott Wilbur**, a new member of the Davis group in 2012, is working primarily with Mulhearn on the search for magnetic monopoles, while supporting the L1 trigger both as an on-call expert and in the development of new algorithms for the trigger upgrade.
- **Dr. Shalhout Z. Shalhout** has transitioned from the CDF experiment, where, working predominantly with Erbacher, he led the effort on the SM Higgs search in the $\ell\ell b\bar{b}$ channel (presenting the Tevatron's Higgs results at ICHEP 2012), and published the first low-mass dark matter search at a collider using monojets. Shalhout is now contributing to the CMS search for the Higgs boson decaying to tau pairs under the direction of Prof. Conway, and working on the CMS forward pixel project.

In addition, four postdoctoral researchers have very recently departed the group, and their work is also described in this report: Dr. Christian Veelken (now a research scientist at Ecole Polytechnique in Palaiseau, France), Dr. Thomas Schwarz (now a professor at the University of Michigan), Dr. Ricardo Vasquez Sierra, and Dr. Maria Assunta (Susy) Borgia.

Graduate Students

In 2011 the first set of CMS students finished their PhD dissertations, using the first physics data from the LHC: Evan Friis is now a postdoc on CMS at the Univ. of Wisconsin, Madison, and Sho Maruyama is now a postdoc on CMS at Fermilab. In 2012 the Davis group saw the completion of four students: David Cox on CDF, and James Dolen, Tia Miceli, and Carley Kopecky on CMS. This represents the subsiding of the wave of students who passed through the group in the past several years, and leaves us with five continuing students, plus new students entering in the fall. We typically have had a steady state of about nine students, approximately two per full faculty member FTE at any moment, ideally at different stages in their graduate careers. We typically rotate students to CERN for a one- to two-year period during their tenure with the group, giving them important exposure to the actual detector and hardware, and introducing them to the international community in the field.

1.3 Recent Highlights

The past year has clearly been exciting in terms of the sheer volume of physics output from the CMS experiment, with over 100 published physics papers. Papers to which the UC Davis group has contributed substantially include those listed in the table below. In 2012 the experiment expects to at least double this number.

Another measure of the involvement of our group members is the talks they are awarded at international conferences. Our group has given many such talks in the past year, listed in the table below.

1.4 CMS Physics

In early 2011 our group had completed analyses of the first LHC data sample of 36 pb^{-1} at 7 TeV, and was publishing papers based on that. Since then CMS has collected and analyzed over a hundred times as much at 7 TeV, and has recorded over 20 fb^{-1} at 8 TeV, with final papers emerging soon. It is exceedingly rare at the energy frontier, and tremendously exciting and challenging, to see such an enormous and rapid growth in the available data sets.

All of our effort at UC Davis is going into analyses searching for new particles and phenomena, including for the Higgs boson, dark matter, supersymmetry, and new heavy quarks and gauge bosons. Nevertheless, except for the observation of a SM-like Higgs boson with a mass of 125 GeV, none of the searches at the LHC have revealed evidence for new particles or phenomena beyond the standard model (SM).

To us, the message of this is that the nature of the new physics may be subtle, and its discovery will require new ideas and approaches. In this section we show that this is precisely our strategy in moving forward into the era of LHC discoveries: bringing novel ideas and methods to bear on the ever-increasing data from the LHC.

Recent Published Papers

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
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,Phys. Lett. B. 716 (2012) 30.
Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson searches at the Tevatron, Phys. Rev. Lett. 109 (2012) 071804.
Search for anomalous $t\bar{t}$ production in the highly-boosted all-hadronic final state, JHEP 09 (2012) 029.
Search for a light pseudoscalar Higgs boson in the dimuon decay channel in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. Lett. 109 (2012) 121801.
Search for Supersymmetry with Like-Sign Lepton-Tau Events at CDF, Phys. Rev. Lett. 110 (2013) 201802.
A Search for a Doubly-Charged Higgs Boson in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C72 (2012) 2189.
Search for neutral Higgs bosons decaying to tau pairs in pp collisions at $\sqrt{s}$=7 TeV, Phys. Lett. B 713 (2012) 68.
Search for t' Pair Production in the Lepton+Jets Channel, Phys. Lett. B 716 (2012) 103.
A Search for Dark Matter in Events with One Jet and Missing Transverse Energy in pp-bar collisions at sqrt(s) = 1.96 TeV, Phys. Rev. Lett. 108 (2012) 211804.
Search for Dark Matter and Large Extra Dimensions in pp Collisions Yielding a Photon and Missing Transverse Energy, Phys. Rev. Lett. 108 (2012) 261803.
Search for the standard model Higgs boson decaying to a bb pair in events with two oppositely-charged leptons using the full CDF data set, Phys.Rev.Lett. 109 (2012) 111804.
Search for the standard model Higgs boson in the decay channel $H \to ZZ \to 4\ell$ in pp collisions at $\sqrt{s}$=7 TeV, Phys. Rev. Lett. 108 (2012) 111804.
Search for Physics Beyond the Standard Model Using Multilepton Signatures in pp Collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B704 (2011) 411.
Measurement of $W\gamma$ and $Z\gamma$ production in pp collisions at $\sqrt{s}$=7 TeV, Phys. Lett. B 701 (5) 2011.
Search for Neutral Minimal Supersymmetric Standard Model Higgs Bosons Decaying to Tau Pairs in pp Collisions at $\sqrt{s}$=7 TeV, Phys. Rev. Lett. 106 (2011) 231801.
Search for a Heavy Top-Like Quark in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.96 TeV, Phys. Rev. Lett. 107 (2011) 261801.
Measurement of the Inclusive Z Cross Section via Decays to Tau Pairs in pp Collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 08 (2011) 117.

1.4.1 Search for New Physics with Photons

Postdoc Chauhan and graduate students Kopecky, Miceli and Stolp worked with Tripathi in analyzing "Photon+X" final states in order to investigate a variety of new phenomena. The strategy focused on a high energy photon in the final state, which is used as the main triggering particle. Accompanying away-side system provides a rich set of final states to be exploited. Using the 2011

Invited Talks at Conferences and Workshops

"The Hunt for the Higgs Boson", J. Conway, plenary talk, Fundamental Physics Conference, Santa Cruz, CA, January 2013.
"Standard Model Tests", R. Erbacher, plenary talk, SUSY 2012, Beijing, August 2012.
"Lepton Identification at CMS in the Boosted Regime", J. Pilot, BOOST 2012, Valencia, Spain, July 2012.
Search For the Higgs Boson at the Fermilab Tevatron", S. Shalhout, plenary talk, ICHEP 2012, Melbourne, July 2012.
"Fourth Generation Quark Searches in CMS", R. Vasquez-Sierra, invited seminar University of Gottingen, Germany, April 2012.
"CMS Pixel Detector, Current Status and Upgrade", R. Vasquez-Sierra, invited seminar LPC Topic of the Week, Fermilab National Laboratory, Batavia, IL, March 2012.
"Searches for Heavy Fourth Generation Quarks in CMS", R. Vasquez-Sierra, plenary SEARCH 2012, College Park, MD, March 2012
"Hunting the Higgs Boson Using the Cholesky Decomposition of an Indefinite Matrix ", J. Smith, VII Taller International Tecnolaser 2012, Havana Cuba, April 2012.
"Boosted Top Quark Analyses at CMS", J. Pilot, Top Physics: From Charge Asymmetry to the Boosted Regime, CERN, Geneva, Switzerland, May 2012.
"2011: A Higgs Odyssey", M. Chertok, All four 8th Grade Science Classes, Emerson Jr. High School, Davis, CA, Dec. 2011.
"SUSY Searches with Taus at CMS", M. Chertok, SUSY Workshop, Berkeley, CA, Oct 2011.
"Search for Exotic Doubly Charged Higgs in Leptonic Final States at CMS", M. Chertok, DPF, Providence, RI, Aug. 2011.
"The Higgs Boson: A Tale of Two Cities", M. Mulhearn, Public Lecture, Davis, April 2012.
"Low mass Higgs searches at the Tevatron", M. Mulhearn, CIPANP 2012, St Petersburg FL, June 2012.
"Recent Results from a Search for Dark Matter Production in the CMS Experiment", M. Tripathi, UCLA Dark Matter 2012, Los Angeles, February, 2012.
"Bump-bonding for the 3D Track Trigger Concept", M. Tripathi, Workshop on the Upgrade of the CMS Detector, Fermilab, Batavia, IL, November 2011.
"A Search for Dark Matter in jet/γ+MET Final States with the CMS Detector", T. Miceli, PASCOS 2012, Merida Mexico, June 2012.

data set (5 fb^{-1}), we have studied the following signatures:

ADD Graviton	$pp \to \gamma + G \to \gamma + E_T^{miss}$
Dark Matter (DM)	$pp \to \gamma + \chi + \bar{\chi} \to \gamma + E_T^{miss}$
Anomalous Gauge Couplings	$pp \to \gamma + Z$; with $Z \to e^+e^-, \mu^+\mu^-, \nu\nu$

The first two of these analysis have been published[1]. Kopecky has graduated with a thesis on DM and Miceli with a thesis on ADD. An earlier version of limits on anomalous gauge coupling has been published[2], and a new combined analysis is in the CMS submission process. The limits placed on dark matter production using the monophoton final state ($\gamma + E_T^{miss}$) represent the first

[1] Phys. Rev Lett. **108**, 261803 (2012)
[2] Phys. Lett. **B701**, 535-555 (2011)

Invited Talks at Conferences and Workshops (Cont.)

"Searches for SM Higgs in $H \to bb$ at CMS", S.Z. Shalhout, Workshop on Interpreting Emerging Higgs Data, University of Oregon, April 2012.
"A Search for Dark Matter in the Monojet+Missing Transverse Energy Signature in 6.7/fb at CDF", S. Z. Shalhout, KICP Light Dark Matter Day, University of Chicago, Nov. 2011.
"Searches for Large Extra Dimensions, Leptoquarks and Heavy Quarks at CMS", S. Chauhan, DIS 2012, Bonn, Germany, March 2012.
"Boosted Objects and Jet Tagging in CMS", R. Erbacher, US ATLAS Hadron Final State Forum, SLAC, November 2011.
"Search for the Higgs Boson in CMS", J. Conway, PANIC 2011, Cambridge MA, July 2011.
"Search for New Physics in CMS", J. Conway, lecture at TASI 2011, Boulder, CO, June 2011.
"Search for New Physics in CDF", J. Conway, lecture at TASI 2011, Boulder, CO, June 2011.
"The Compact Muon Solenoid at the Large Hadron Collider", R. Breedon, invited public lecture at the Commonwealth Club of California, San Francisco CA, May 2011.
"Top Quark Physics at the Tevatron", R. Erbacher, APS 2011, Anaheim CA, May 2011.

such analysis to be done at a hadron collider. The first results were presented by Tripathi at the high profile UCLA Dark Matter Symposium in 2012. Following that, we organized a workshop on the topic of DM at colliders, and its relationship with the direct searches for DM, at UC Davis in April 2012.

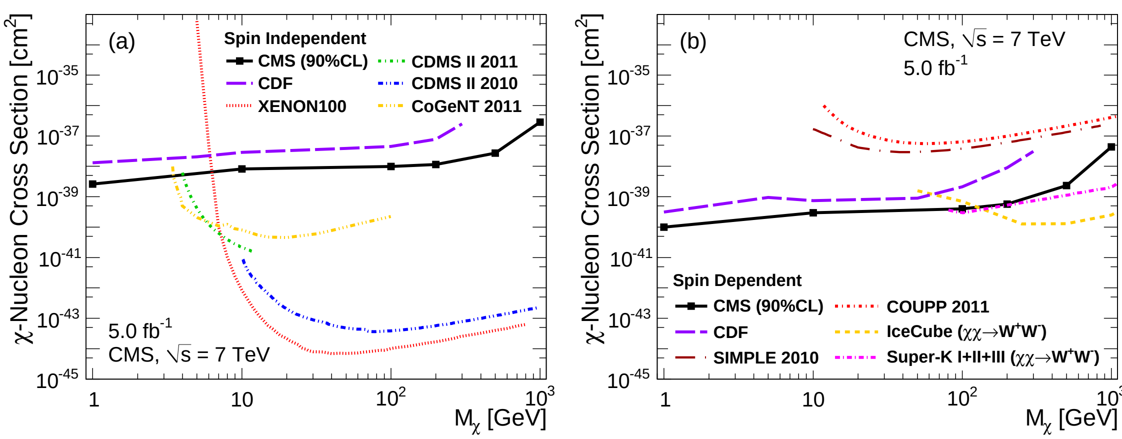

Figure 1: Upper limits on cross section for χ-nucleon elastic scattering as a function of χ mass for spin-independent (left) and spin-dependent (right) cases.

At the LHC, DM can be directly produced and is accessible via $q\bar{q} \to \gamma\chi\bar{\chi}$ where the photon is produced through radiation emitted by the incoming quarks, and the DM particles result in E_T^{miss}. Recent theoretical work has cast this process in terms of a massive mediator particle in the s channel that produces a $\chi\bar{\chi}$ pair. Figure 1 shows the upper limits on χ-nucleon cross section as a function of χ mass. In the spin-independent case, we have extended the sensitivity into the low mass region which is inaccessible to direct search experiments due to threshold effects. In the spin-dependent case we have improved the limits over a large mass range.

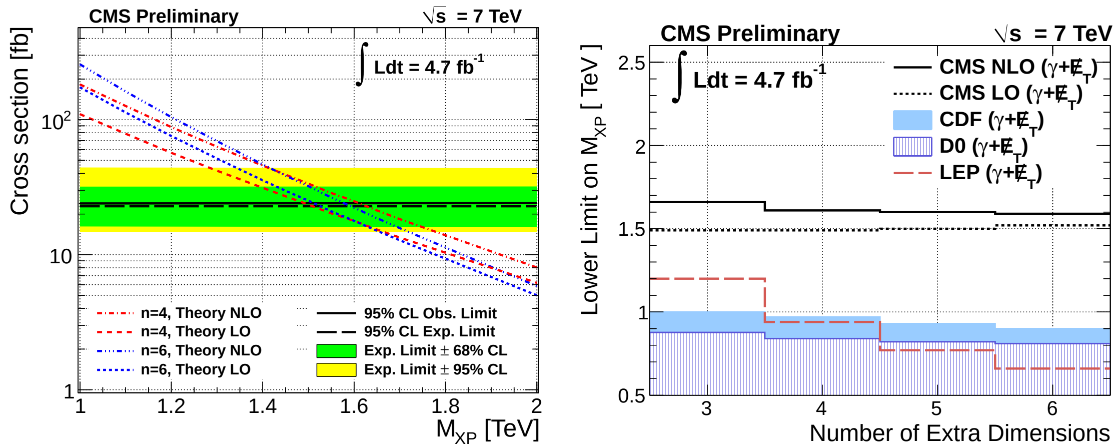

Figure 2: (Left) Theoretical predictions and observed/expected limits on the ADD graviton production cross section as a function of M_{XP}. (Right) Limits on M_{XP} as a function of the number of extra dimensions. CMS has already improved upon the Tevatron.

In the ADD framework, the observed weakness of gravity is a consequence of the universe having n large (compacted at sub-mm scale) extra dimensions. Within this context, we searched for the associated production of the Graviton and photon, which results in a monophoton final state. Figure 2(left) shows the theoretical cross section as a function of M_{XP} and the expected and observed limits. On the right is our exclusion curve for ADD, showing a significant improvement over the Tevatron results.

1.4.2 Searches for New Physics Using Top Quarks

Introduction

The LHC, with the completion of the data collection run in 2012, has produced a large sample of top quarks which can be used to further enhance the sensitivity of searches for new physics beyond the Standard Model. UC Davis has taken a leading role in several of these searches, and its group members are also highly involved in the optimization of specialized substructure algorithms that are used to indentify and reconstruct boosted top quarks, which increase in prevalence in the high-energy regime that will be extended even further with the upcoming run at a center-of-mass energy of 14 TeV. This section describes the accomplishments of the group, as well as plans for the future, in the area of searches for new physics utilizing top quarks.

Resonances decaying to Boosted Tops

Predicted heavy particles such as Kaluza-Klein gluons and Z' bosons are predicted to have strong couplings to the top sector, and therefore have a large decay rate into top anti-top pairs. The top quarks produced from these heavy particles are highly boosted in the lab frame, resulting in a particular event topology: the top decay products are highly collimated. In some cases, all of the decay products of the top will be reconstructed within one 'fat' jet. The 'fat' jet uses a larger distance parameter during the clustering of particles during event reconstruction. This object is known as a "boosted top jet". In other cases, the decay products of the W boson are merged within a single 'fat' jet, but the b quark remains to be reconstructed in an additional jet. UC Davis were leaders, along with JHU, in the development and commissioning of the CMS top-jet and W-jet tagging algorithms which are used to identify these objects.

Erbacher and Conway, working with postdoc Vasquez and UC Davis graduate Dolen (now with SUNY Buffalo), worked to pioneer these techniques to identify boosted top quarks and boosted W bosons using jet substructure. Using these tools, the first ever search for high mass resonances using boosted top quark jet identification was carried out with the data collected in 2011, at a center-of-mass energy of 7 TeV. These results were published in JHEP in early 2012.

The search was recently updated and extended to use the 2012 LHC dataset consisting of nearly 20 fb^{-1}, collected at a center-of-mass energy of 8 TeV. Postdoc Pilot, under the direction of Professors Erbacher and Conway, and in collaboration with UC Davis graduate Dolen and others, led the analysis effort to commission the substructure algorithms and techniques in this new dataset. Many updates to the analysis techniques were necessary due to the difficult running conditions, including increased luminosity and underlying event activity. A requirement imposed on the rapidity difference between the two selected boosted top jet candidates served to significantly enhance the analysis sensitivity to high mass resonances. Figure 3 shows the distribution of the top candidate pair invariant mass after the full analysis selection.

With this distribution, we test for the presence of several different models of new physics, including RS KK gluons, and both wide and narrow Z' resonances. Observing no significant excess of events, we extend further the exclusion limits set using 2011 data. We exclude wide (narrow) Z' particles with masses up to 2.35 (1.7) TeV/c^2, and RS KK gluons with masses up to 1.8 TeV/c^2.

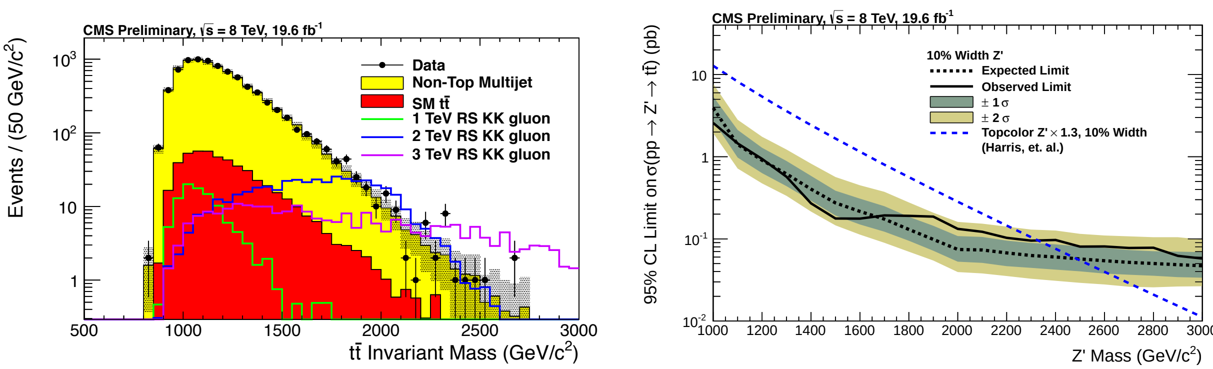

Figure 3: Left: The top pair invariant mass spectrum observed in the full 2012 dataset collected by CMS. Example signal distributions are shown in the colored lines. Right: The 95% CL upper limits on the product of production cross section (σ) and branching fraction (B) of a Z' boson into a top quark pair, as a function of the resonance mass, shown for the wide resonance hypothesis.

We currently are working to combine the results of this all-hadronic analysis with similar searches in the lepton+jets channel, with the intent to submit the combined analysis results to PRL in the near future. Longer term, we are working to update the all-hadronic analysis to use several new techniques, including subjet b-tagging, N-subjettiness, and others, which will further enhance the mass reach of this analysis.

Improving Boosted Top Reconstruction

With the increased center of mass energy in the upcoming LHC run and beyond, new physics processes may have enhanced cross sections, increasing the reach of current searches. Additionally, the increased luminosity and number of interactions per bunch crossing provide challeneges to maintain the effectiveness of current algorithms. UC Davis is continuing its leadership in developing and implementing new analysis tools and methods for enhanced discovery potential using boosted top quarks. This includes a high degree of participation and leadership in the Snowmass project, which is currently taking place in the United States to study the future of particle physics. Professor Erbacher is currently serving as a convener of a working group tasked to study top quark reconstruction at current and future collider experiments. Postdoc Pilot is also serving as a contact person for a sub-group, participating in and organizing studies specific to boosted top reconstruction algorithms, along with any possible detector effects which may play a role.

Some early conclusions have been presented at Snowmass meetings held over the past few months. Looking to the future 14 TeV center-of-mass energy run of the LHC, the number of pileup interactions per beam crossing will likely exceed 100. In this environment, pileup activity significantly degrades the efficiency of boosted top jet reconstruction algorithms, while allowing for an increased contribution of QCD jets. The jet mass peak also is shifted to large values, above 200 GeV/c^2.

To maintain sensitivity, one may consider using a jet grooming algorithm, such as pruning (used for the W-tagging algorithm at CMS) or trimming[3]. These jet grooming algorithms aim to remove soft and large angle radiation during the jet clustering process. This both reduces the QCD contamination of jets in the top-tagging algorithm selection, as well as corrects the top jet mass peak (and improves its resolution) by removing the additional pileup contributions.

Preliminary results from the top reconstruction algorithms sub-group have been submitted to the arXiv online as a white-paper, and will be included in the final report to be produced after the Snowmass project concludes.

In addition to the Snowmass project, which is not specifically geared toward any one experiment or collider scenario, work has been underway to improve the algorithms used for reconstruction of boosted top quarks at CMS. These studies are currently in the CMS approval process and should be ready to present at the 2013 BOOST conference, held in August. Postdoc Pilot and UC Davis graduate Dolen are participating in this effort.

Some of the algorithms under study for improving the CMS top tagging algorithm include the jet grooming methods described above, as well as N-subjettiness, and the application of subjet b-tagging.

The N-subjettiness algorithm has been proposed[4] as a way to enhance discrimination of heavy, boosted particles which are reconstructed into a single jet. The algorithm determines the consistency of jet constituents with a hypothesized number of subjets, using a p_T-weighted distance from the set of subjet axes being tested. For example, a top quark jet should be consistent with three subjets, so the particles should be clustered near the three subjet axes being tested, resulting in a low value of the 3-subjettiness, τ_3. The ratio τ_3/τ_2 has been shown to provide high discrimination of top quark jets.

The application of b-tagging algorithms to identified subjets within top candidate jets can dramatically reduce the multijet contribution to the background of searches using the top tagging algorithm. With the commissioning of the subjet b-tagging application being done currently, we hope to use this in updates to searches for new physics.

Search for t' and b' in Lepton Plus Jets

The SM contains three generations of fermions, yet it is reasonable to ask whether there could

[3]D. Krohn, J. Thaler, L-T. Wang, JHEP 1002:084 (2010)
[4]J. Thaler, K. Van Tilburg, JHEP 1103:015 (2011)

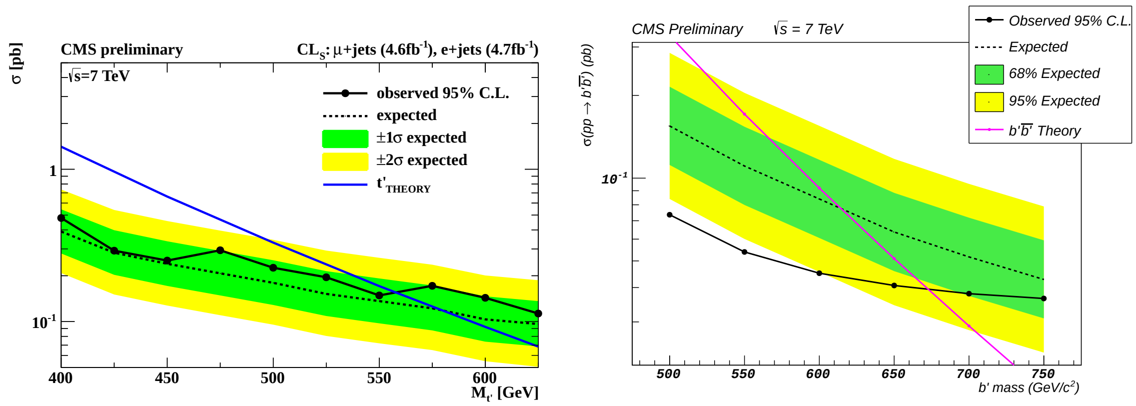

Figure 4: Observed (solid line with points) and expected (dotted line) 95% CL upper limits on the (left) $t'\bar{t}'$ and (right) $b'\bar{b}'$ production cross section as a function of the t' and b' quark mass for the combined e+jets and μ+jets channels. The $\pm$ 1 and $\pm$ 2 standard deviation ranges on the expected limit are shown by the green and yellow bands. The theoretical cross section is shown by the continuous line.

be more than three. Current experimental constraints require a corresponding fourth generation neutrino to be massive: heavier than half the mass of the Z boson. The mass splitting between the t′ and the b′ quarks is favored to be smaller than the mass of the W boson. Assuming sufficient mixing between the third and fourth generations, the dominant decays for fourth generation t′ and b′ quarks are therefore $t' \to bW$ and $b' \to tW$ respectively. With the discovery of a Higgs boson near 125 GeV, a fourth generation can be less likely in some theories, but many theories now predict the existence of new vector-like t′ and b′ quarks having similar signatures. The UC Davis group, led by Erbacher and Conway, working with postdoc Vasquez and, recently, also postdoc Pilot, has been one of the main driving forces in these searches for such fourth generation quarks in CMS. The searches are done in the “lepton+jets” decay channel, therefore requiring an identified charged lepton, missing transverse momentum, and at least four jets with high transverse momenta.

In the search for $t' \to bW$ quarks using LHC data collected in 2011, the UC Davis group, working with KSU, was particularly responsible for the electron+jets final state analysis. The search strategy was inspired from Erbacher's initiation of the similar search in CDF at the Tevatron, which was then performed by D0 as well. We first attempt to reconstruct the mass of the t′ using a kinematic fit and setting the hadronically decaying t' mass equal to the leptonically decaying one by combining objects in the event. We also define the event H_T as the scalar sum of the transverse momenta of the lepton, the jets and the missing transverse momentum, which serves as a generic variable that gives the energy scale of the object. We then search for the existence of a t′ quark by looking for deviations in the two dimensional H_T versus the resulting M_{fit} mass distribution. Combined with the muon+jets channel the observed limit on the existence of t′ is 565 GeV/c^2. Postdoc Vasquez played a major role in this search and presented the pre-approval talks for both the EPS 2011 result, and the updated result with the full 2011 dataset. This result excludes a fourth generation of fermions up to a critical mass at which their weak interactions become non-perturbative. Fig. 4 shows the results from this search, which has been published in PLB.[5]

Postdoc Vasquez, working with Erbacher, has also been one of the main analyzers in the CMS $b' \to tW$ search in the lepton plus jets channel. This time, the variables we use to distinguish

[5]Phys. Lett. B 718 (2012) 307

between signal and SM processes are the event H_T and the classified event jet multiplicity, which increases the discriminating power for our signature. We test for the presence of $b'\bar{b}'$ production in data. We can conclude, from the theoretical expectation, that b′ quark masses below 670 GeV are excluded.

Furthermore, there are new physics models that include the existence of fourth generation vector-like (non-chiral) quarks (denoted B, T) that could decay through Flavor Changing Neutral Current (FCNC) processes. For these kinds of quarks with a new Yukawa coupling, the decays $T \to tZ$ and $T \to tH$ could be dominant, where H is the Higgs boson. Using the same analysis strategy as in the b' search, we search for pair-produced $T\bar{T}$. We find no evidence for this signal, so we find the upper limit in the production cross section of such particles. Our 95% C.L. upper limit on the $T\bar{T}$ production cross section (not shown) excludes T vector-like quark masses below 625 GeV. The results of this analysis have been published in JHEP. [6]

The combination of techniques used in boosted object reconstruction and vector-like quark searches has been used in a new search for vector-like B quarks. Depending on the mass of the vector-like B quark, the final state can contain several boosted objects, including W, Z, and Higgs bosons. The CMS W-tagging algorithm has been extended for this search to identify boosted Z and Higgs bosons in addition to W bosons. For this search, the number of identified boosted objects are counted and used to categorize events into regions of differing signal-to-background ratio. The H_T distribution within each category is used to further discriminate signal events in a shape-based analysis. Figure 5 shows some distributions of the H_T for different event categories. Postdoc Pilot has been contributing to this new search, lending the expertise relevant to boosted object identification. The analysis is currently undergoing the approval process and we hope to present the results publicly soon.

Leadership in Top Searches

UC Davis has had multiple personnel serve in leadership roles within the new B2G (Beyond the 2nd Generation) Physics Analysis Group on CMS. Erbacher is currently serving as co-convener of the XTY subgroup, one of two subgroups within B2G. The XTY Group is responsible for all top- and bottom-partner searches, including fourth generation, vector-like, FCNC, and so forth. It also includes various other top-like searches including 5/3 charge and searches using razor variables. Postdoc Pilot has served as B2G liaison to the Jet/MET physics object group, specializing particularly on jet substructure used for top- and W-tagging. In this role, he reviews analysis techniques in use, and provides recommendation and support for analysts wishing to use existing techniques.

1.4.3 Search for the Higgs Boson

With the large new data samples at the LHC, the search for the Higgs boson has arguably seen the most dramatic result: the discovery of a new bosonic state at 125 GeV, with production and decay patterns consistent with that od the long-sought Higgs boson predicted in the standard model. Using the 10 fb^{-1} sample at 7 TeV and 8 TeV, as of spring 2012, and combining the results from some eight different search channels, the CMS and ATLAS experiments both obtained nearly 5σ evidence for the new state.[7]

The UC Davis Group has played a strong role in this search, particularly in the search for the tau pair decays of the Higgs. As of the discovery, this mode had not been seen definitively, but

[6] JHEP 01 (2013) 154

[7] Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,Phys. Lett. B. 716 (2012) 30.

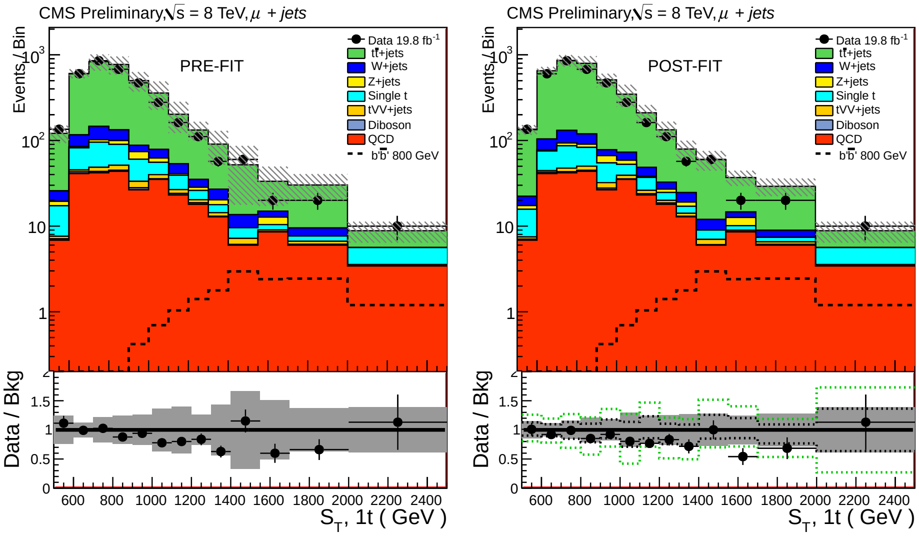

Figure 5: Results of the event selection for the vector-like B search which includes boosted object identification. The H_T distribution is shown before (left) and after (right) the fitting procedure performed during limit setting, for events containing 1 boosted W, Z, or Higgs boson. Expected signal is shown in the dashed black line. This plot is preliminary and has not been officially approved, but is presented here for illustration.

with the full 24 fb^{-1} dataset, a nearly 3σ excess has been observed in preliminary analyses. Final results are expected to emerge in late 2013.

While it might seem that the observation of the Higgs boson is the end of this long quest, it is really only the beginning of a long program at the LHC of measuring the Higgs boson mass and couplings, and testing whether it is in fact one of the many Higgs bosons predicted in models beyond the standard model.

The UC Davis group is involved in several aspects of the Higgs boson search, including the search for SM $H \to ZZ$, SM/MSSM $H \to \tau\tau$, and the searches for NMSSM $a \to \mu\mu$, and $H \to aa \to 4\tau$ decribed below.

SM/MSSM $H \to \tau\tau$

For over a decade Conway has been a pioneer in the seach at hadron colliders for enhanced production of the neutral Higgs bosons predicted in supersymmetry, first at CDF in Run 2 at the Tevatron, and now at the LHC. The most sensitive channels, experimentally, are those involving final state decays to τ pairs.

In two-Higgs-doublet models, including the MSSM, there are three neutral Higgs bosons predicted: the light scalar h, the heavy scalar H, and the pseudoscalar A. The masses and couplings of these particles are governed by two model parameters, usually taken to be m_A and $\tan\beta$ (the ratio of the vevs of the two Higgs doublets). When $\tan\beta$ is large, O(10-50), the couplings of all three neutral Higgs bosons to down-type quarks and leptons is enhanced by a factor proporional to $\tan\beta$. Since they are predimantly produced via their coupling to b quarks, the production cross section is proportional to $\tan^2\beta$.

Working with student Evan Friis and postdoc Veelken, starting several years efore the LHC turn-on Conway led the development of two key components of this search at the LHC: improved

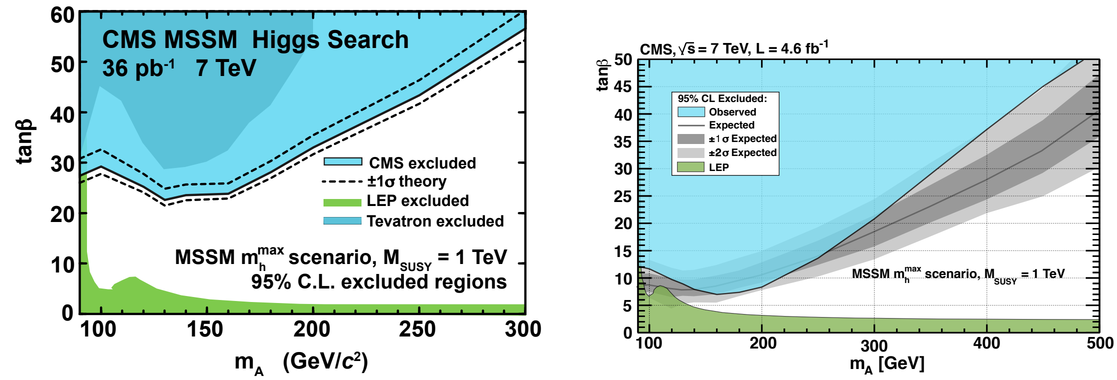

Figure 6: Evolution of the CMS bounds on the MSSM parameter space of $\tan\beta$ versus m_A from the first 36 pb^{-1} data sample (left) to the full 4.6 fb^{-1} sample at 7 TeV (right).

tau ID (called TaNC) based on particle flow and neural network discrimination, and a dramatically improved algorithm for tau pair mass reconstruction, called SVfit.

With the very first 36 pb^{-1} data sample collected in 2010, CMS was able to attain exclusion bounds in the MSSM parameter space that were signiicantly better than those achieved at the Tevatron, as shown in the left panel of Fig. 6. The paper on this analysis, edited by Conway, was one of the first few Higgs results published by CMS and appeared in Phys. Rev. Lett. Then, as the large data sample accumulated in 2011, additional seach subcategories were used and ultimately yielded limits on the MSSM shown in the right hand panel of Fig. 7. The paper on this work, early versions of which were edited by Conway, was published in Phys. Lett. B.

At the time of the announcement of the observation of a SM-Higgs-like boson decaying to $\gamma\gamma$ and ZZ in July 2012, the data from 7 TeV and 8 TeV running were combined in the search for SM Higgs decaying to tau pairs. Figure 7 shows the tau pair invariant mass distribution (based on SVfit), and the resulting upper bounds on SM Higgs in this final state.

With the full 2012 dataset at 8 TeV the tau pair mode is of major interest in testing whether the observed boson is indeed SM-like, decaying to fermion pairs at the SM rate. The tau pair mode will continue to be the most sensitive probe of the MSSM Higgs sector. Conway and postdoc Shalhout, are pushing toward the analysis of associated production of Higgs and vector bosons, with the Higgs decaying to tau pairs, including the all-hadronic modes. Preliminary results have indicated a 3σ excess in this channel, and we expect results to emerge in late 2012 from this work leading to publication in early 2013.

SM $H \to ZZ$

The Higgs search channel $H \to Z^0Z^0 \to 4$ leptons is an important discovery channel for the Higgs at the LHC, as evidenced by the observation results in 2012. Senior researcher Smith has made a number of contributions to this analysis within CMS.

A key geometric property of such a decay is that the four charged tracks in the decay emerge from a single point. Several methods are under investigation which take advantage of this property to select good events and reject various backgrounds: Method 1) demand that all four tracks are within four units of impact parameter significance $|\text{SIP3d}| < 4$ (based on the b-tagging algorithm) of the selected offline primary vertex; Method 2) pre-select four tracks that are all within tolerances in $|Dxy| < 0.5$ cm and $|Dz| < 1.0$ cm of the same offline vertex and subsequently apply the

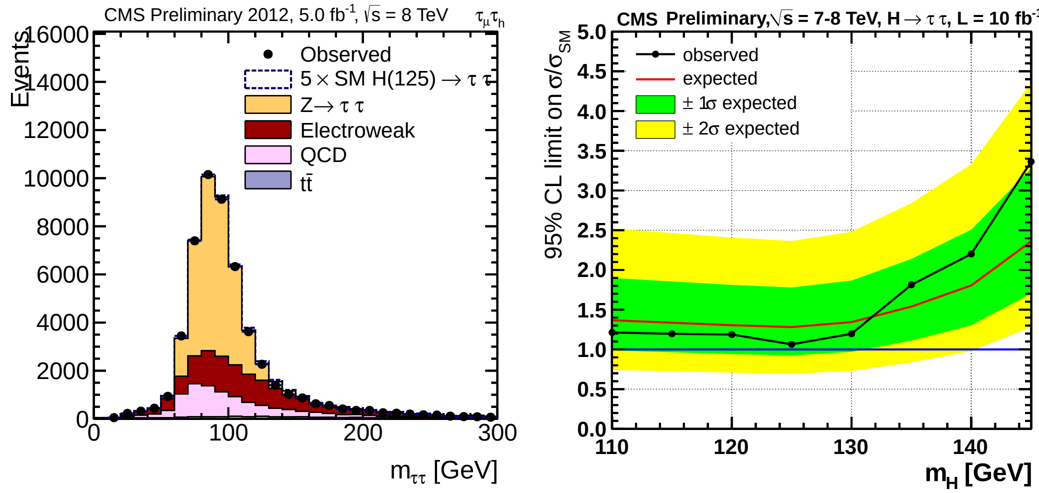

Figure 7: Left: Tau pair invariant mass distribution in the $\mu\tau$ final state. Right: Exclusion bounds on SM Higgs cross section ratio as a function of Higgs boson mass from combined SM tau pair search channels.

|SIP3d| < 4 cut; Method 3) demand that all four tracks form their own vertex and apply a cut on the χ^2 of the fit to the hypothesis that the four tracks emerge from the same spatial location. Methods 1) and 2) are similar and require the position of the primary vertex along with the four tracks. Method 3) does not require knowledge of the primary vertex and only compares the four tracks to each other and has been developed by John Smith.

The ZZ decay mode to four leptons ($eeee$ or $ee\mu\mu$ or $\mu\mu\mu\mu$ is also particularly sensitive to the spin/parity of the Higgs boson. Using the discovery data sample, Conway co-edited a paper on this topic, which ruled out the pseudoscalar hypothesis at the 95% CL.[8]

NMSSM $a \to \mu\mu$

The Next-to-Minimal Supersymmetric extension of the Standard Model extends the MSSM by introducing a complex singlet superfield which necessarily contains a scalar field component. The added scalar field expands the Higgs sector to three CP-even scalars (h_1, h_2, h_3), two CP-odd scalars (a_1, a_2) and two charged scalars (H^+, H^-). Borgia (former postdoc), Chertok, Gunion, and graduate student Ricci-Tam initiated, led, and completed a search for a light a produced via gluon fusion through a quark loop, decaying into two oppositely charged muons in the invariant mass range around the Υ resonances at the Compact Muon Solenoid (CMS). Our results, based on 2011 data corresponding to an integrated luminosity of 1.3 fb^{-1} recorded with a dedicated, low-p_T dimuon trigger that we (Borgia) commissioned expressly for this analysis, were shown at Moriond, and are now published in PRL. Gunion is, of course, a theoretical expert in NMSSM Higgs physics, and provided both guidance and detailed calculations to achieve these results. As an exception, he is listed as an author on the paper.

Fits to the sidebands around the Upsilon resonances show no significant signal contribution, so we determine 95% CL upper limits on $\sigma Br(pp \to a \to \mu\mu)$ as a function of the dimuon mass using the CLs approach. Resulting limits are significant in the context of the NMSSM in terms of upper limits on $|\cos\theta_A|$. Figure 9 presents upper limits as a function of m_{a_1} for $\tan\beta = 1, 2, 3, 10, 30$, and

[8] 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

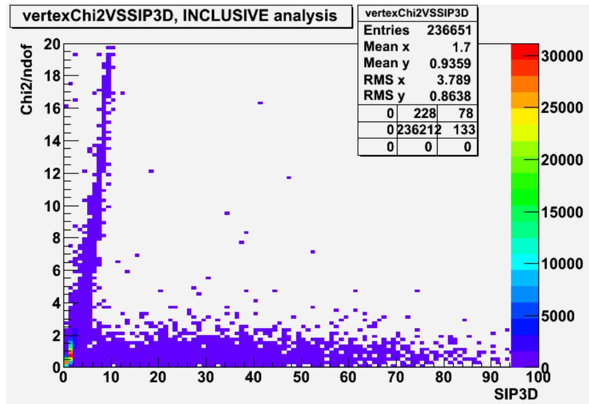

Figure 8: Left: The χ^2/ndof from 4-track vertex fit versus largest |SIP3d| in the 4-track set.

50. Our upper limits are compared to an earlier analysis of the BaBar $\Upsilon(1S)$ and $\Upsilon(3S)$ data[9], and are superior for $m_{a_1} \geq 7.5$ GeV for $\tan\beta = 50$, decreasing to $m_{a_1} \geq 6$ GeV for $\tan\beta = 2$, and are superior for all masses at $\tan\beta = 1$. Further, these are the only limits available in the $m_{a_1} > m_{\Upsilon(3S)}$ mass range.

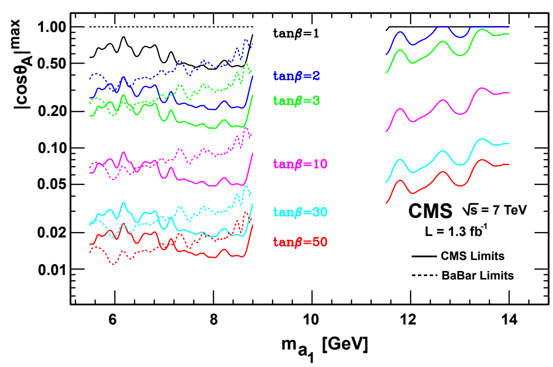

Figure 9: Upper limit on the NMSSM parameter $|\cos\theta_A|$. The different solid curves correspond to different $\tan\beta$ values. For each $\tan\beta$ value in mass range 1 the second, dotted curve shows the limits from the BaBar Υ analysis.

Search for NMSSM $H \to aa \to \tau\tau\tau\tau,\ \tau\tau\mu\mu$

The search for the direct production of the a is limited in the 2012 dataset and beyond due to triggering considerations, and insensitive to preferred $a \to \tau\tau$ decays. Thus, our current research instead focusses on vector boson associated production of the NMSSM Higgs boson H, followed by its decay into two a, both of which then decay leptonically, either into a pair of tau leptons or a pair of muons. This work is being performed by UC Davis physicists Chertok, Gunion, Ricci-Tam (graduate student), Tos (graduate student), Yohay (postdoc), three undergraduates, and with the

[9] R. Dermisek and J. Gunion, “New constraints on a light CP-odd Higgs boson and related NMSSM Ideal Higgs Scenarios”, PRD 81, 075003 (2010).

participation of two CMS collaborators from Korea. The UC Davis group has made substantial contributions to hadronic tau triggering and reconstruction, at both CDF and CMS, and Conway is interested in this analysis as well. As was the case for the 2011 analysis, Gunion's theoretical guidance and calculations will be crucial.

In this scenario, the decay products of the light a pseudoscalars will typically be highly boosted and overlapping, resulting in substantial challenges for the reconstruction.[10] Figure 10 shows the Feynman diagram for this process.

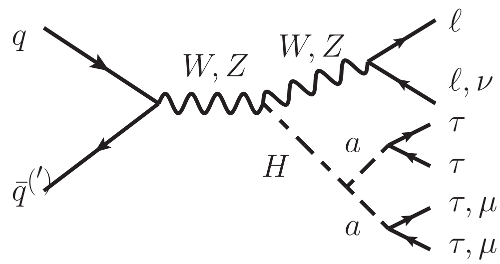

Figure 10: Feynman diagram for NMSSM Higgs associated production with cascade decay at the LHC. In the NMSSM, for $m_a \sim m_\Upsilon$, $Br(a \to \tau\tau) \gg Br(a \to \mu\mu)$.

Overlapping τs are particularly problematic, as has been shown in a previous study at CDF in 2009 by Wilbur. Therefore, modified algorithms for τ identification and other new selection criteria are being developed, with substantial progress in 2013. We define "di-tau" objects that allow 1 or 3 charged particles in the signal cone of the highest-p_T τ_h candidate, to account for the decay products of the partner τ. Invariant mass, impact parameter, and total charge restrictions can be added to the identification, using a likelihood technique being developed by students Tos and Ricci-Tam and postdoc Yohay. We are also investigating the use of jet substructure techniques for these purposes, and currently analyzing the 2011 and 2012 data for an upcoming result.

1.4.4 Search for New Physics with Kinked Tracks

Conway, Smith and graduate student Squires have been developing a novel technique to detect heavy unstable charged particles. This technique works by taking particle tracks in the CMS silicon tracking detector and pairing them. The algorithm calculates the distance of closest approach of the end point of a candidate parent track to the closest point on a prospective daughter track. This three-dimensional distance is then required to be very small in order to find pairings of tracks most likely to in fact be from the same point in space, and thus originate from decays in flight. Clearly the algorithm will find many such track pairings originating from nuclear interactions and/or hard scatters. The algorithm further requires charge conservation and can utilize dE/dx information to suppress background.

This search is highly flexible and enables the group to look for a diverse set of signals including AMSB and sequential fourth generation leptons. With its immediate applicability to several exotica searches the new technique is well motivated. The group is also developing a complimentary technique to separate signal from noise as an add on module to the main technique to allow for scanning the multidimensional mass hypothesis space available to many of the exotica searches targeted. This enables the group to do the traditional setting of limits on specific models most

[10] Note that it is still possible that the SM-like Higgs observation reported by CMS and ATLAS at 125 GeV is, in fact, the NMSSM h_2 boson. Detailed branching fraction measurements are needed to uncover its identity.

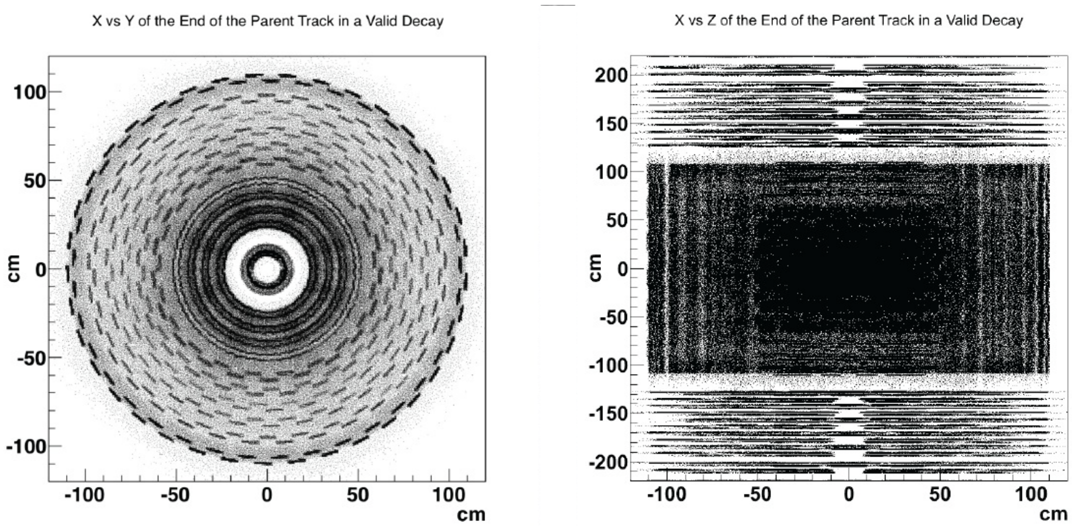

Figure 11: Position in x-y (left) and r-z (right) of track pair decay candidates. Most of the candidates arise from nuclear interactions or hard scatters, which gives rise to the "pion tomograph" of the CMS tracker.

desired to be probed by the physics community, in addition to probing less likely models with relative ease. The main technique is also data-driven using two standard model processes (charged kaon and pion decay) and hence not subject to bias introduced by looking only at Monte Carlo of signal.

As an example of the power of the technique, Figure 11 shows what is essentially a "pion tomograph" of the CMS tracker. The heavier concentrations of identified track pairs correspond to the locations of the detector planes in the barrel region, which is expected for decay candidates which are in fact coming from nuclear interactions or scattering.

Using 2012 data a number of different searches will be performed using the decay finding tool, leading to a number of future publications.

1.5 CMS Detector and Operations

1.5.1 CSC Detector Performance (Senior Researcher Cox)

Dr. P.T. Cox has been responsible for CSC offline software since 1998, and has been the convener of the CSC Detector Performance Group (DPG) in CMS since June 2009. For 2012 he was appointed CSC Deputy Project Manager in CMS, in support of the CSC Project Manager, Prof. Jay Hauser (UCLA).

The detection, reconstruction, and triggering of muons was a cornerstone to the goals of CMS in searching for the Higgs boson as well as for physics within and beyond the Standard Model. The crucial tasks of the CSC project are to ensure that muons are detected in the endcap regions of CMS, to provide reconstructed muon hits and muon track segments (straight lines built from the hits in an individual CSC) for use in the high-level trigger (HLT) and offline, and to deliver segment information (trigger primitives) to the CSC Level-1 (L1) trigger hardware track finder (so that it can provide muon candidate tracks to the CMS central trigger.) The CSC DPG must ensure that the CSC detector provides optimal muon data for physics analyses, and must monitor the quality of the raw and reconstructed data and the quality of the trigger primitives. As convener, Cox provides

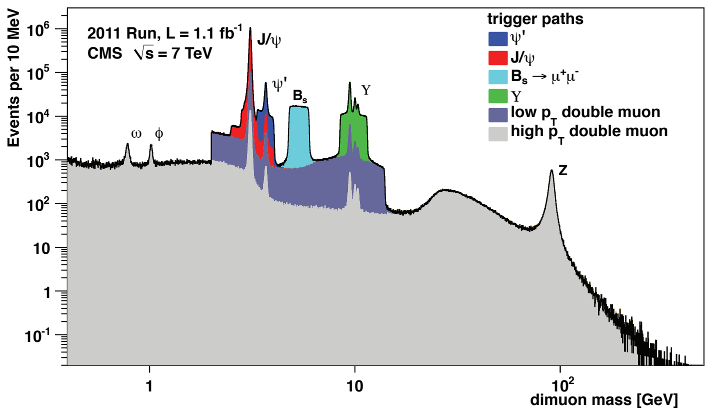

Figure 12: Invariant-mass spectrum of opposite-sign muon pairs in CMS integrated over the full muon acceptance $|\eta| < 2.4$ for an integrated luminosity of 1.1 fb^{-1} at $\sqrt{s} = 7$ TeV. This results from the superposition of various dimuon trigger paths.

oversight and direction of all topics under the auspices of CSC DPG. He is the primary contact for all offline CSC issues, including software, reconstruction, simulation, calibration, data quality and monitoring, and data certification. He must closely follow the data collection and simulation activities of CMS, in order to promptly address any offline CSC-related problems, and this involves tight interaction with the CSC Detector Operations group, and with the other Muon groups within CMS.

LHC running culminated in the collection by CMS during 2012 of almost 22 fb^{-1} of pp collisions data at $\sqrt{s} = 8$ TeV. The performance of the CMS muon system in LHC running since 2010 has been excellent. After three years of operation, only 3% of the almost 0.5 M channels in the CSC system suffered failures that could not be repaired without opening the detector (only now being done during the 2013-2014 LHC shutdown.) The redundancy of the system ensured that overall muon track reconstruction efficiencies nevertheless remained uniformly high. The gradual increases in beam energy and pp luminosity in LHC required progressive adaptation of the CMS muon triggers, but overall muon detection, reconstruction, and triggering continued to work with great success, up to the highest pp instantaneous luminosities of 8×10^{33} cm^{-1} s^{-1}, at $\sqrt{s} = 8$ TeV. Backgrounds were held to acceptable levels, and trigger thresholds were maintained sufficiently low to satisfy the broad physics program of CMS. Pile-up increased dramatically as luminosity increased (reaching 35 events per bunch crossing at luminosity 7.5×10^{33} cm^{-1} s^{-1}) but still did not seriously impede muon triggering or reconstruction. The CSC DPG has measured the efficiencies for segment reconstruction and trigger primitive generation, and they remain high (at the level of 95% or above) and independent of trigger rate and instantaneous luminosity. The spatial resolution of the CSCs remained good, in the range of about 60 μm to 140 μm depending on the CSC type, in accordance with the CMS technical design for the muon system, and did not degrade as luminosities increased.

The overall performance of CMS for muon reconstruction is neatly demonstrated by Fig. 12, which shows the opposite sign dimuon invariant-mass distribution obtained from data collected in 2011[11].

Currently, CSC DPG work is concentrated on development of the CSC software for, and simulation of, the post-2013/4 shutdown upgraded CSC system.

[11] CMS physics results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

1.5.2 CSC System (Senior Researcher Breedon)

UC Davis has been a major contributor to the Endcap Muon System (EMU) of CMS since 1992, its main efforts involving the cathode strip chamber (CSC) detector system, including electronics development, reconstruction software, commissioning, and operations. Research Physicist Richard Breedon was the first Operations Manager of the CSC system and organized the on-call expert shift crew that has around-the-clock responsibility for the operation of the detector during physics and cosmic-ray data taking. Problems that arise with the CSC system that are beyond the scope of the central shift team are handled by a call to the CSC Detector-On-Call (DOC; formerly CSC Expert Operator (CEO), the concept of which Breedon originated and implemented in 2008). Breedon is also responsible for the software geometry description of the entire CMS endcaps (steel, chambers, and shielding) that is used by the simulation and analysis software CMSSW and the visualization programs.

For the past ten years Breedon has served as Chair of the Muon Editorial Board. He reviews and often edits all CMS Notes, Internal Notes, and Conference Reports related to the CSCs, barrel drift tubes (DT), endcap and barrel resistive plate chambers (RPC), and muon alignment systems. Breedon was the chief editor of a comprehensive paper[12] detailing the performance of all the CMS muon systems based on collision data. Cox was lead author for the CSC system.

1.5.3 CSC System (Erbacher)

During LHC running, Erbacher and postdoc Pilot contributed to the CSC Prompt Feedback group, which was expected to examine and validate CSC data on a short timescale whenever CMS recognized interesting or potentially exciting physics events, in which all sub detector behavior was carefully reviewed. Pilot also served as a DQM shifter for the CSCs, and underwent training to become a CSC DOC (Detector On Call) expert in which capacity he served at the end of LHC running, and will continue in this role at the beginning of LHC running in 2015. Erbacher, Pilot, and Shalhout are involved in the 2013–2014 CSC upgrade project, working on cathode front-end electronics board (CFEB) testing and repair. These analog CFEBs, removed from the ME1/1 chambers that are receiving new digital CFEBs, are being repurposed for use on the new ME4/2 CSCs. In addition, Erbacher, with student Dolen, has worked on the muon local reconstruction, specifically developing parameterized expressions for reconstructed muon hit uncertainties in the CSCs.

1.5.4 EMU Upgrades (Tripathi, Breedon, Erbacher)

For the CSC upgrade project, 72 chambers of the ME4/2 type are being constructed at CERN and the on- and off-chamber electronics for the ME1/1 chambers are being upgraded. During the long shutdown (LS1) of the LHC, scheduled for February 2013 to late in 2014, Breedon and CSC Upgrade Manager R. Loveless (Wisconsin) will supervise the installation, cabling, and commissioning of the new ME4/2 chambers on the endcap steel disks of CMS. During the ME4/2 installation, Erbacher, on sabbatical at CERN through July 2013, and postdoc Pilot, stationed at CERN are involved in commissioning the new detectors, debugging read-out, and developing both monitoring and simulation. With the complete set of ME4/2 chambers in the trigger, a manageable Level-1 trigger rate will be achievable with a lower p_{T} threshold.

For the ME1/1 electronics upgrade, UC Davis (Breedon and Tripathi, with engineers) produced 80 expanded low voltage monitoring boards (LVMB), which are part of the on-chamber electronics.

[12] "The performance of the CMS muon detector using pp collisions at $\sqrt{s} = 7$ TeV at the LHC", MUO-11-001, (submitted to the Journal of Instrumentation)

For the new design of the ME1/1 cathode front-end boards (CFEB), the number of CFEBs increased from 5 to 7, so the number of channels served by the LVMB for ME1/1 also increased from 5 to 7. The upgraded LVMB also had to be compatible with the new design of the DAQ motherboard, which is digital with an optical fiber readout (O-DMB). The interface between the LVMB and the O-DMB is accomplished by reusing existing CSC signal ("skewclear") cables, improving noise rejection for the communication path by providing more ground connections and using differential signaling. Use of the skewclear cables also necessitated modifications to the LVMB to accommodate a larger cable connector and the addition of the differential driver and receiver. Engineering support and ordering was provided by our departmental electronics engineer. During development, several prototype boards were delivered or sent to CERN to be tested on on an ME1/1 chamber on a test stand. UC Davis also produced and delivered LVMB cables for the new ME4/2 chambers that will be installed toward the end of 2013.

The ME1/1 test setup consists of a spare ME1/1 chamber instrumented with prototypes of the upgraded CFEBs (7 total), LVDB, and LVMB, in combination with a peripheral crate housing an O-DMB and O-TMB. The O-TMB represents a significant upgrade to the existing trigger motherboard, supporting optical control and trigger readout of the new CFEBs. The test setup serves as the central platform for integrated testing of the upgraded on-chamber (CFEB, LVDB, LVMB) and off-chamber (O-DMB, O-TMB) electronics. Erbacher, and postdocs Shalhout and Pilot, have contributed significantly to the ME1/1 test setup, providing operational support and aiding in the development of control, monitoring, and test software. The test software, developed at the ME1/1 test setup, will be used to certify the functionality of the upgraded electronics on each of the 72 ME1/1 chambers prior to installation on the CMS detector. A preliminary version of the test software was used to demonstrate the complete functionality of the on-chamber electronics during a June 2013 CMS review. With functionality established, authorization was received to begin removing the previous electronics from ME1/1 chambers in preparation for the upgrade.

1.5.5 Forward Pixels

The UC Davis group has contributes in a number of ways to the CMS Forward Pixel (FPIX) construction, installation, and operation over the past several years. This work is led by Conway and Chertok, with students and postdocs. We describe here some of our recent contributions and future activities in the FPIX project.

P5 Clean Room Preparation

Postdocs Yohay and Borgia, student Ricci-Tam, and Chertok, Conway contributed to the construction of the pixel clean room lab at P5 in late 2012 ad early 2013. The CMS forward pixel detector (FPIX) was extracted by the UC Davis group in May 2013 to access the beampipe and for small repairs and maintenance of the detector during the long shut down. In this situation, the pixel detector must be placed in a refrigerated clean room environment. It is not desirable, and no longer feasible due to radiation levels, to transport the detectors back to the tracker integration facility (TIF) at the main CERN site. Therefore, a clean and climate controlled room is under construction at the CMS experimental site, Point 5, in room SHL-5. Borgia was one of the leaders of this project until she left the group in January 2012, and new postdoc Yohay has taken on this project starting this summer, working with colleagues from UC Riverside and CERN. The clean room is roughly 10×13 m^2 and hostas two cold boxes ("coffins") for the FPIX and two cold boxes for the barrel pixels (BPIX), several desks and repair workbenches as well as a wire bonder and all the electronic racks necessary to control and readout the detector for tests. A schematic is shown in Figure 13.

A water-glycol chiller keeps the detectors cold for storage, while a C_6F_{14} chiller will be used to cool the detectors during repairs. Most of the equipment from TIF was transported to this new room and has been commissioned successfully.

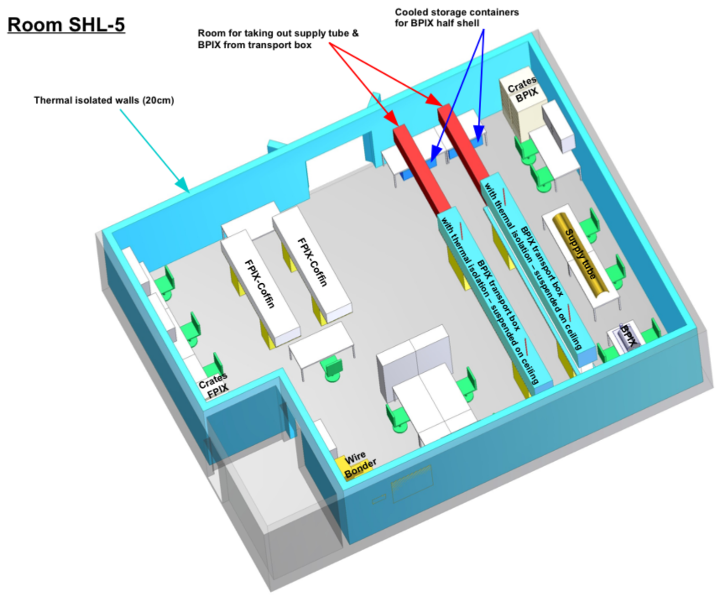

Figure 13: Schematic of P5 clean room showing the FPIX coffins and the BPIX transport boxes.

FPIX Deinstallation/Reinstallation

A major responsibility of the UC Davis group in the CMS Forward Pixel (FPIX) project has been the transport of the four completed detector half cylinders (HC) from the CERN Meyrin TIF site to the LHC P5 collision hall near Cessy, France, followed by their installation into the CMS central tracker. Working with FNAL engineers, Conway and Physics Department Development Engineer John Thomson designed and constructed the apparatus necessary to accomplish this delicate task, which was performed in both 2008 and 2009. The work was carried out in close cooperation with with the barrel pixel detector (BPIX) and the beam condition monitor (BCM) installation teams. Conway led this effort at Davis. Resident leadership at CERN was provided by Chertok during his sabbatical in the 2007-08 academic year with support by postdoc Ricardo Vasquez Sierra and graduate students Evan Friis and Matthew Searle. Photos from the first installation are shown in Fig. 14. Conway led the team in extracting the detector successfully in May 2013.

FPIX Data Acquisition System

Graduate student Michael Squires has also been working with the pixel subsystem team. He has been Pixel DOC (detector on call) for several weeks this year and will continue to be DOC for the remainder of the LHC running period before the long technical stop and upgrade phase. He took over TTC lead from Ben Kries of Cornell and is also lead for the Pixel Function Manager online software. In early 2012 he contributed to the SLC 5 port of the online software codebase. He's also repaired the RAID/NAS for the pixel system test stand at the TIF. He has given one talk on behalf of the pixel system for 2012 recommissioning.

Squires has been asked to be DAQ this coming year and plans to do so for the remainder of running period. He will be lead for (and has already worked on) QPLL monitoring of pixel systems for central monitoring. He was a part of the SEU coding team and will be continuing to work on this project in the immediate and foreseeable future. He has also been asked by Danek Kotlinski

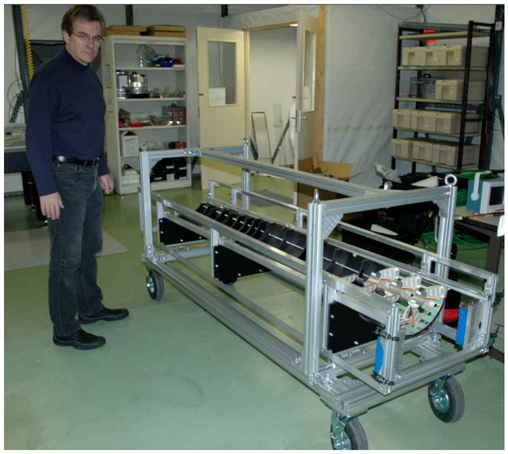 

Figure 14: Left: FPIX cylinder transport unit at TIF. Right: FPIX installation.

(PSI) to begin completion of a list of online tasks and check over the multithreaded code base as he is knowledgeable in this area.

1.5.6 Online Beam Spot Measurement and Monitoring (Chauhan)

To measure the properties of reconstructed tracks precisely, information regarding the primary interaction point in the event is required. The beamspot of two colliding beams can be measured by using reconstructed tracks, which in turn providees feedback to further improve the track and primary vertex reconstruction. The beam spot measurement is characterized by the following parameters: The CMS experiment has a dedicated online beam spot measurement tool and software package that is part of the online Data Quality Monitoring (DQM) system. Until 2011, the full tracking system was used for this measurement, but since 2012 taking data was under very high pileup conditions, which made it difficult to fully reconstruct tracks in real time. Therefore to provide real time information, pixel tracks and vertices were used in 2012 data taking. The quantities were measured as the running average of 5 LSs to accumulate enough data for a stable converging fit, and subsequently, the measurements were monitored for each LS in the online DQM by the CMS shift crew. Figure 15 shows an example of a measurement of the beam spot x, y, and z positions and size during data taking in 2012. Postdoc Chauhan was the key member of the beam spot monitoring group. He also ensured that the same tools were also used for Pb–Pb collisions in the heavy ion program.

1.5.7 LHC Phase II Tracker

We have participated in R&D studies with FNAL and other institutions on a replacement silicon tracker for CMS to allow for triggering on high p_T tracks in the high-intensity running era of the LHC (SLHC). The basic idea of this proposal is to deploy some number of special triggering layers within the silicon tracker. Each trigger layer will feature two doublets of silicon strip detectors separated radially by about 1 cm. Within each trigger layer the combinations of doublet hits that are consistent with high P_T tracks are identified and passed on to higher level logic units. Each doublet will consist of a stack of sensors on either side of an interposer and readout chip, a so-called double stack. The UC Davis group has made mandrels and carbon fiber lay-ups for mechanical structures (Chertok) and has assembled "double-stack" prototypes using advanced interconnect technologies

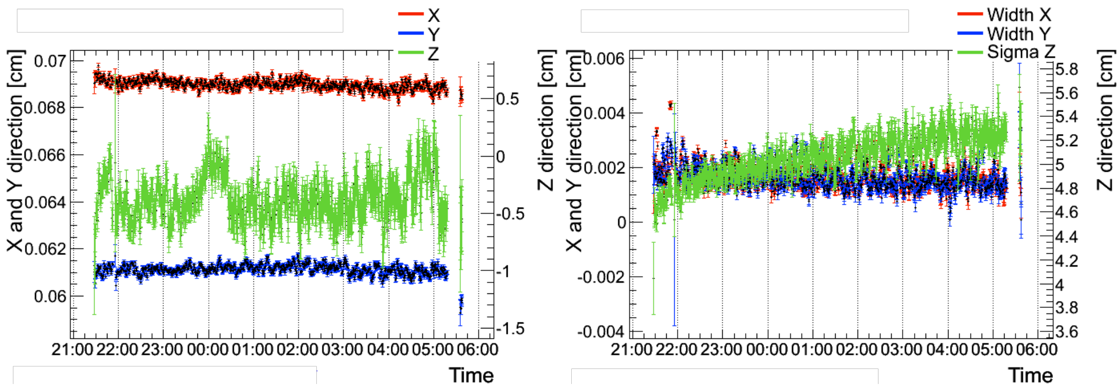

Figure 15: Luminous region position (left) and size (right) during a long LHC pp fill.

(Tripathi).

1.6 CDF Physics

In September 2011, the Tevatron ended over 25 years of operations at the energy frontier. The UC Davis group has completed an active research program at the Fermilab Tevatron, and has been a leading contributor in the CDF collaboration's effort to observe production of SM and MSSM Higgs bosons. In addition, UC Davis researchers have published the Tevatron's final word on electroweak SUSY gaugino production, published the first ever search for the direct production of dark matter particles in Tevatron $p\bar{p}$ collisions, and for new heavy top-like quarks. We document here our accomplishments in the past several years.

1.6.1 SM Higgs Search

Observation of Higgs boson production is among the primary goals of high energy experimental physics, and would shed light on the nature of electroweak symmetry breaking. In the past few years, direct searches by the LHC and Tevatron experiments have closed much of the previously allowed range of Higgs mass (m_H) between the LEP limit ($m_H > 114.4$ GeV) and the bound inferred from measurements of precision electroweak observables ($m_H < 152$ GeV).

The LHC experiments reported in July 2012 an excess of events with a significance of roughly five standard deviations, considered a Higgs discovery, centered around a value of $m_H \sim 125$ GeV. While a SM Higgs boson of this mass is predicted to decay to a pair of b quarks ($b\bar{b}$) 58% of the time, LHC sensitivity is primarily derived from searches for the subdominant decay modes $H \to \gamma\gamma$, $H \to W^+W^-$, and $H \to ZZ$. At the Tevatron, sensitivity to a low-mass Higgs boson ($m_H \leq 135$ GeV) is mainly due to searches for $H \to b\bar{b}$, in which the combined CDF and D0 searches now report an excess of roughly 3 σ, which constitutes "evidence" of this new particle decaying to a pair of b-quarks.. As such, the Tevatron searches are of fundamental interest since observation of the Higgs boson in the $H \to b\bar{b}$ mode would demonstrate that the Higgs boson is the source of fermion masses and allow for the measurement of a quark Yukawa coupling.

The Tevatron excess, and hence the evidence for the Higgs, is driven by the CDF search for production of the Higgs boson in association with a Z boson in the process $p\bar{p} \to (Z \to \ell^+\ell^-, H \to$

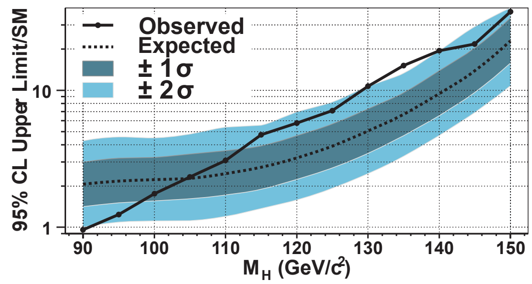

Figure 16: Expected (dashed curve) and observed (solid line) ZH cross section upper limits divided by the SM cross section as a function of the Higgs boson mass.

$b\bar{b}$) (ℓ = electron or muon). The latest CDF result [13] in this mode reports a broad excess for $110 < m_H < 150$ GeV with a maximum significance of roughly 2.1 σ for $m_H \sim 135$ GeV as displayed in Fig. 16.

UC Davis postdoc Shalhout, working with Erbacher, maintained a significant involvement with the CDF $ZH \rightarrow \ell^+\ell^- b\bar{b}$ analysis group. As part of his doctoral thesis new Davis postdoc Pilot developed muon identification and ZH discriminant algorithms for the CDF $ZH \rightarrow \ell^+\ell^- b\bar{b}$ search. Shalhout was among the leading contributors to the CDF $ZH \rightarrow \ell^+\ell^- b\bar{b}$ search, providing leadership and technical expertise as co-convener of the CDF $ZH \rightarrow \ell^+\ell^- b\bar{b}$ subgroup for more than two years. His efforts in this search channel have been aimed at maximizing signal acceptance and background rejection through, increased lepton reconstruction efficiency, optimal application of CDF b-jet identification algorithms, and the use of advanced multi-variate discriminants. Shalhout also performed the extraction of limits and produces much of the public documentation of the $ZH \rightarrow \ell^+\ell^- b\bar{b}$ results. Shalhout contributed to the wider CDF Higgs boson search in his role as the Higgs Group Monte Carlo Coordinator, responsible for generating the simulated Higgs samples used by all other CDF Higgs searches. The Davis group led the effort to publish the $ZH \rightarrow \ell^+\ell^- b\bar{b}$ result.

1.6.2 SUSY Search with Like-Sign Lepton-Tau Events

Chertok and Robert Forrest (previous graduate student) searched for SUSY phenomena using the CDF II detector at the Fermilab Tevatron, and have recently published the result in PRL. The search assumes electroweak associated production of the lightest chargino and second-lightest neutralino, via a single W boson-mediated s-channel Feynman diagram. This is equivalent to an assumption of heavy squarks. Charginos decay promptly into a single lepton through a slepton $\tilde{\chi}_1^\pm \rightarrow \tilde{l}^{(*)}\,\nu_l \rightarrow \tilde{\chi}_1^0\,l^\pm\,\nu_l$ and neutralinos similarly decay into two detectable leptons $\tilde{\chi}_2^0 \rightarrow \tilde{l}^{\pm(*)}\,l^\mp \rightarrow \tilde{\chi}_1^0\,l^\pm\,l^\mp$. We assume that at least one lepton is a tau. Since this search does not assume strong production of colored squarks and gluinos, and because it specifically probes tau-dominated SUSY parameter space, it is complementary to the searches performed so far at the LHC.

We require detection of an electron or muon plus a hadronically-decaying tau lepton and that the lepton and tau have like-sign (LS) electric charge. The LS requirement is a powerful tool for SM background rejection. This search is model-independent in that the signature is generic in SUSY models, and has sensitivity for high $\tan\beta$ due to the dedicated tau reconstruction. UC Davis researchers created the "lepton+track" triggers used for this analysis and have contributed

[13] arXiv:1207.1704v2, accepted to PRL.

substantially to the hadronic tau identification at CDF. Data observations are well-described by SM background expectations, and we set limits in simplified gauge and gravity-mediated SUSY models. A representative limit contour is shown in Fig. 17 for the simplified gauge model.

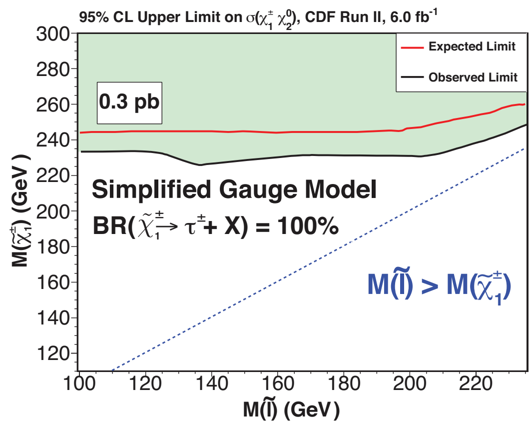

Figure 17: Expected and observed limit contours at 95 % confidence level in the simplified gauge model. The shaded region is excluded for $\sigma(\tilde{\chi}_1^\pm \tilde{\chi}_2^0) \leq 300$ fb.

1.6.3 DM Monojet Search

The UC Davis group produced the first collider limits on dark matter production in events with one energetic jet and significant missing transverse energy (the monojet + missing E_T signature). This work involved close collaboration of postdoc Shalhout with Erbacher, former postdoc T. Schwarz (now at U. Michigan) and with the Fermilab theory group [14], and as a result produced strong bounds on the dark matter production rate which were directly comparable to those obtained in direct detection experiments. Initial studies for the search were performed by Schwarz, with Shalhout performing the actual analysis under supervision of Erbacher after Schwarz's departure from the UC Davis group.

Collider searches are not limited by the detection threshold for low-energy nucleon recoil which restricts the sensitivity of direct detection experiments to low mass ($1 - 10$ GeV) dark matter. Further exploration of this mass range is of particular interest due to recent results from CRESST-II, CoGeNT and elsewhere which suggest an excess of events above background expectations that is potentially consistent with low mass dark matter. [15] Shalhout designed novel methods for modeling the dominant background from QCD multijet processes and enhanced the sensitivity of the analysis to a dark matter signal through artificial neural network background rejection.

The CDF result observes no excess of events in this range above the expectation from background processes and presents limits on the dark matter production rate as bounds on the dark matter-nucleon scattering rate. These bounds are shown in Fig. 18 for various models of dark matter production along with bounds from leading direct detection searches. This result introduced the first presentation of collider bounds on dark matter production in a manner easily comparable to results from direct-detection experiments. This presentation facilitates cross-field comparison of results and has been adopted by recent CMS searches for dark matter, described above. The CDF

[14] B. Yang, P. Fox, and R. Harnik, J. High Energy Phys. 12 (2010) 048.
[15] G. Angloher et al., arXiv:1203.1576; C. E. Aalset et al., Phys. Rev. Lett. 106 (2011) 131301.

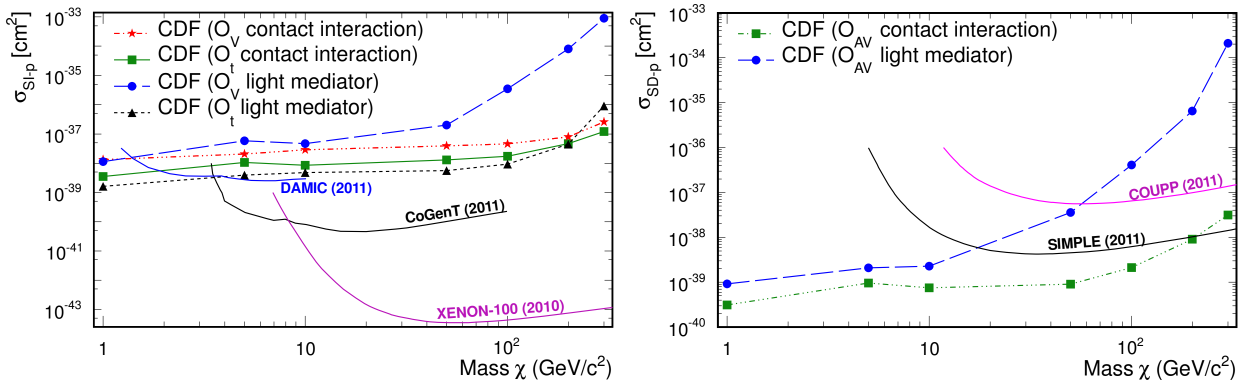

Figure 18: Comparison of CDF results to recent results from direct detection dark matter searches. Spin-independent (left) and spin-dependent (right) bounds on dark matter-nucleon scattering cross sections are shown for the operators $\mathcal{O}_{AV}$, $\mathcal{O}_V$, and $\mathcal{O}_t$, assuming contact interactions. For comparison we also display CDF bounds assuming that dark matter production is mediated by a light ($\sim$ 100 GeV) particle.

results were presented by Shalhout at a Fermilab Joint-Theoretical Seminar in January of 2012, and have recently been published in PRL.

1.6.4 Search for t'

Several theoretical models hypothesize the existence of a fourth generation top-like quark, such a quark could decay to a W boson and a down-type quark mimicking the decay of the top quark and blending into the top quark signal. Although LEP direct searches for neutrinos and precision fits to the electroweak observables do restrict the space for such a quark they leave significant space for physically interesting models and theorists have constructed several such models ranging from formulations of supersymmetry and grand unified theory candidates to simple extensions involving only one extra family of quarks and leptons. In addition, vector-like top partners are popular in many models now that a low-mass Higgs has likely been discovered.

The UC Davis search for a t' quark decaying via $t' \to Wq$ has produced world's best limits for decays to generic quarks and to specifically b quarks. Erbacher initiated this search as the first of its kind at the Tevatron, and members of the group have continued this search up through 2011. Most recently, student David Cox has written his thesis on this search, under the direction of Erbacher, and in collaboration with Conway, postdoc Schwarz, and former Davis postdocs Alison Lister (now UBC) and Andrew Ivanov (now KSU).

The search has utilized the expertise and toolset developed in the CDF Top Group and Schwarz to accurately reconstruct the mass of the searched-for quark and combines this with the scalar sum of the energies in the event (H_T) to perform a 2D binned likelihood fit. With these techniques the challenging task of separating the t' signal from the nearly identical top background and setting limits is made possible. The results of this search excluding a fourth-generation t' quark decaying to $Wb(Wq)$ with mass below 358 (340) GeV at 95% CL, were published in Phys. Rev. Lett. as the then-best limits on a t' quark and the first published limits on a t' quark decaying specifically to a b quark.

1.6.5 Top Forward-Backward Asymmetry

The measurement of the $t\bar{t}$ forward-backward asymmetry, which was the original Ph.D. thesis of Davis postdoc Schwarz, has been the subject of two publications, each with over 100 citations. Erbacher and Schwarz have continuously updated this measurement in collaboration with group members from the University of Michigan. The asymmetry has remained large at near 15±6%, and with a significance of over two standard deviations from zero. Interestingly, the asymmetry shows a strong dependence on the mass of the top-antitop system ($M_{t\bar{t}}$), where for events with $M_{t\bar{t}} > 450$ GeV have an asymmetry of 48% with a significance of 3.4 standard deviations from zero. This is shown in Figure 19.

In addition to the original measurement, Schwarz contributed to a similar measurement of the asymmetry in an independent channel of top quark events in which both W bosons decay to leptons (dilepton channel). Surprisingly, the measurement in the dilepton channel has also been significantly larger than predicted by three standard deviations (42±16%), confirming the original result.

Recently the D0 experiment has has confirmed the large asymmetry in the CDF results in the lepton+jets channel. The D0 measurement, $A_{FB} = 20 \pm 6\%$, is three standard deviations from zero. (They do not see a significant asymmetry in the dilepton channel.) A plot summarizing the above results is shown in Figure 19, including a combination of CDF results which was performed by Schwarz.

Currently, the measurement of the forward backward asymmetry is one of the few true anomalies in the high energy physics. The LHC has not confirmed similar anomalies in their version of the charge asymmetry, which is a bit different. These Tevatron measurements have been the topic of over a hundred theoretical citations and numerous articles in scientific media.

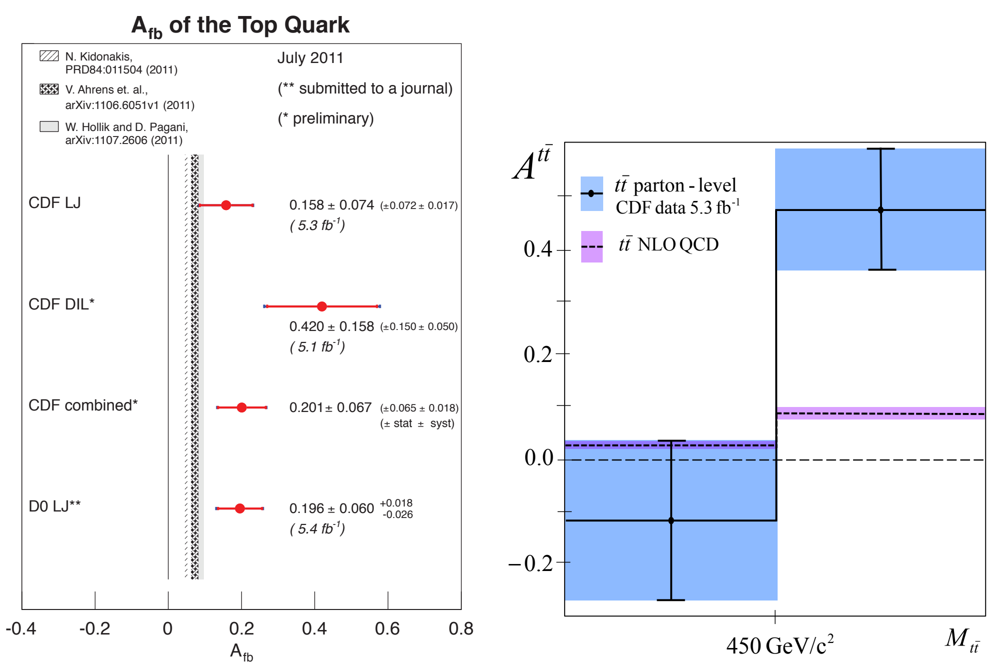

Figure 19: Left: comparison of CDF and D0 measurements of $t\bar{t}$ FB asymmetry. Right: mass dependence of the observed asymmetry in CDF.

2 Task B1: Overview

The faculty of Task B1 include Steve Carlip (gravity) and the model builders/phenomenologists Hsin-Chia Cheng, John F. Gunion, Markus Luty and John Terning. The gravity and phenomenology groups will give separate overviews below. Suffice it to say that both the gravity group and all members of the phenomenology group have been extremely active for many years, especially during the January, 2010 to April, 2013 period covered by this review. Phenomenology and model building are now being driven by the LHC data —- many exciting observations and limits are emerging, as described later.

Project Objective

Our overall objective is to contribute very significantly to the now very rapid developments in both gravity and phenomenology/model building. More details will be found in the separate sections for gravity and phenomenology.

Developments in both gravity and in phenomenology/model building have been occurring very rapidly. Papers are written and published and new ideas are being developed on a continuing basis. The LHC data has the potential of redirecting the phenomenology and model building efforts at any moment should, for example, the departure of the Higgs signals from SM expectations be confirmed or if supersymmetric signals are detected or excluded to ever higher mass scale.

Task Personnel

The gravity group and phenomenology group will list the personnel involved in their efforts separately. Senior faculty were listed above in the Overview.

Recent Highlights

The gravity group and phenomenology group will present their highlights separately below. Both groups have been exceptionally productive. In the January, 2010 to April, 2013 period, the phenomenology/model building group has produced 68 papers and given 98 conference talks and seminars, while the gravity group has written 22 papers and given 59 conference talks and seminars. Both groups work on the most important main-stream aspects of their respective fields. They generate ideas and explore directions that have substantial impact on their fields and influence the direction of future theoretical developments in many ways.

2.1 Task B1: Gravity

The gravity subgroup of Task B1 consists of one faculty member (Steven Carlip), a postdoc (Henrique Gomes), a contingent of five to eight graduate students, and an REU-funded undergraduate most summers. Since early 2009 we have written 22 papers and a *Scientific American* article, and given 44 conference talks and 15 seminars.

Carlip chaired the gravity subpanel of the 2012 NSF Committee of Visitors. He has just completed terms as Divisional Associate Editor of *Phys. Rev. Lett.* and Editorial Board member of *Proc. R. Soc. London A*, and currently serves on the Editorial Board of *Phys. Rev. D* and the Editorial Advisory Committee of *Class. Quant. Grav.* Six students completed their Ph.D.s in the past three years: Marcus Afshar has a permanent teaching position, Josh Cooperman and Chun-

Yen Lin have very good postdocs, Colin Cunliff has a lectureship, Damien Martin has a visiting faculty position, and Rajesh Kommu has a software position for an NSF-sponsored consortium on geodynamics. Davis hosted the 2013 Pacific Coast Gravity Meeting.

2.1.1 Background

More than eighty years have passed since the first attempts to quantize general relativity. In that time we have learned a great deal—Faddeev-Popov ghosts, the background field method, the effective potential and effective action, the Dirac approach to constrained systems, and string-inspired techniques for calculating QCD amplitudes all originated in attempts to quantize gravity. But the ultimate goal of a complete, consistent theory of quantum gravity remains distant.

The fundamental problems are not just technical. General relativity tells us that gravity is a manifestation of the structure of spacetime, so quantizing gravity means in some sense quantizing space and time. But the foundations of quantum field theory rely on a fixed spacetime background to define such things as causality (which requires fixed light cones) and locality (which requires fixed points). Moreover, simple arguments from the uncertainty principle and the existence of black holes, and more sophisticated studies of the strongly coupled Einstein field equations, suggest that the structure of spacetime may change drastically at the Planck scale.

The main research programs in quantum gravity today are string theory and loop quantum gravity. We have worked in both. Our main philosophy, though, is to look for "windows"—simple settings (black hole horizons), approximations (lattice methods, strong coupling), and models (lower dimensions) that might offer insights without requiring a full-fledged theory of quantum gravity.

2.1.2 Recent Highlights

We describe here some highlights of our work over the past three years.

- **Black hole microstates:** One of the few things we can say with confidence about quantum gravity is that it must explain black hole thermodynamics. The Bekenstein-Hawking entropy is virtually the only equation we know that is truly quantum gravitational, depending on both $\hbar$ and G. As early as 1986, Carlip suggested that the relevant microscopic states might be described by a two-dimensional conformal field theory at the horizon, a proposal that has gained new popularity with the discovery of the extremal Kerr/CFT correspondence.

  We have recently studied the extension of the Kerr/CFT correspondence to nonextremal black holes, and discovered a "clean" and natural set of near-horizon boundary conditions that lead to a correct counting of the degrees of freedom for an *arbitrary* rotating black hole. This represents a major step forward: we can now describe almost every four-dimensional black hole, extremal or not, in terms of a conformal field theory at the horizon.

- **Lattice quantum gravity:** While the ordinary weak field expansion of general relativity is nonrenormalizable, nonperturbative approaches to the path integral may still be possible. One natural candidate is lattice quantum gravity, which, like lattice QCD, might give us valuable information in regimes in which weak field perturbation theory fails.

  In contrast to lattice QCD, where fields live on a fixed lattice, in quantum gravity the field *is* the lattice. Just as a geodesic dome approximates a sphere with flat triangles, a four-dimensional lattice can approximate an arbitrary curved spacetime. This is a technically difficult problem, and until recently it largely failed to give sensible results. But a new formulation, "causal dynamical triangulations" (CDT), seems quite promising: it not only gives the correct cosmological limit, but yields the right lowest order quantum fluctuations.

Our group has published the first truly independent test of these results, using our own code written from scratch. We have confirmed the phase structure, the very good classical limit, and the nature of the volume fluctuations. We have also taken first steps toward applying the method to a popular new extension of general relativity, Hořava-Lifshitz gravity, and have borrowed techniques from the analysis of the cosmic microwave background to study the full spectrum of quantum fluctuations for a lower-dimensional model. Recently we generalized the (2+1)-dimensional code to allow for specified boundary data (rather than periodic boundary boundary conditions), permitting calculations of transition amplitudes.

- **Small scale structure:** An intriguing result of CDT simulations is that spacetime at very short distances seems to undergo a "spontaneous dimensional reduction" to two dimensions. In particular, the spectral dimension—the dimension as seen by a random walker—drops from four to two at a characteristic scale of about 15 Planck lengths. Evidence for similar behavior occurs in several other approaches to quantum gravity as well, including renormalization group flow and high temperature string theory.

  A major focus of our group has been to try to understand this phenomenon. One explanation comes from short distance "asymptotic silence," the collapse of light cones and decoupling of nearby points at very small scales. We have shown that the short distance approximation to the Wheeler-DeWitt equation has this feature, which leads to two-dimensional behavior at small scales. Our preliminary investigation of the effect of quantum fluctuations on light cones has provided further evidence for Planck scale asymptotic silence, and a study of short distance black hole thermodynamics has allowed us to further explore implications.

- **Lower dimensional models:** One of Carlip's long-standing research areas has been the use of lower dimensional general relativity to illuminate basic issues of quantum gravity. Gravity in 2+1 dimensions, in particular, offers a setting in which many technical issues drastically simplify, letting us explicitly implement a number of quantization schemes. Our recent work has focused on topologically massive gravity, a parity-violating higher derivative extension of general relativity in 2+1 dimensions that has attracted wide interest because of its connection to the AdS/CFT correspondence. We have studied the constraint structure and degrees of freedom, subtleties in perturbation theory, and some surprising features in the asymptotic behavior, including the need to extend the standard Fefferman-Graham expansion.

- **Shape dynamics:** Shape dynamics,a model developed by our postdoc Gomes and collaborators, is a reformulation of general relativity that "trades" time reparametrization invariance for a new symmetry, local conformal invariance. While the model is classically equivalent to general relativity, such a dramatic reformulation may offer new avenues for both the classical theory and quantum gravity. In particular, the new symmetry has a much simpler constraint structure than standard general relativity, eliminating some of the more difficult technical problems in canonical quantization. Our recent work has focused on the coupling of matter and an exploration of the vacuum symmetries.

- **Other work:** Thanks to our ability to attract very good students, we have been able to work on several other interesting topics as well. Recent students projects include the role of the Born rule in the quantum mechanics of a multiverse; the semiclassical limit of loop quantum gravity and its application to cosmology; the question of whether quantum gravitational fluctuations of scale imply the existence of a minimum length (they apparently don't); and the appropriate definition of quasilocal gravitational energy in cosmology.

2.1.3 Personnel

Faculty

Steven Carlip, UC Davis

Postdocs

Henrique Gomes (Ph.D., University of Nottingham; started at Davis in September 2011)

Graduate students

Marcus Afshar (Ph.D. 2011; permanent position, Glendale College)
Josh Cooperman (Ph.D. 2013; postdoc, University of Nijmegen, the Netherlands)
Colin Cunliff (Ph.D. 2013; lecturer, UC Davis)
Rajesh Kommu (Ph.D. 2012; Consortium on Computational Infrastructure for Geodynamics)
Chun-Yen Lin (Ph.D. June 2011; postdoc, National Central University, Taiwan)
Damien Martin (Ph.D. June 2011; visiting faculty position, Whittier College)
Charles Pierce (advanced to Ph.D. candidacy spring 2012)
Adam Getchell and Gabriel Herczeg (not yet advanced to Ph.D. candidacy)
Michael Sachs (switched fields to complex systems)

Undergraduates (summer, supported by REU program)

Masha Baryakhtar, 2009 (Harvard; now in graduate school at Stanford)
David Kamensky, 2010 (University of Virginia; now in graduate school at UT Austin)
Christian Anderson, 2011 (Harvard; starting graduate school at MIT)
Jonah Miller, 2012 (Colorado; starting graduate school at Guelph-Waterloo/Perimeter Institute)

2.1.4 Publications and Talks since 2009

Over the past three years, the Davis gravity group has written 22 papers for journals and refereed conference proceedings (11 by Carlip, 3 by Gomes in his first year here, 8 by students), plus a solicited article by Carlip in *Scientific American.* We have given 44 conference talks (18 by Carlip, 4 by Gomes, 22 by students) at a total of 26 conferences, and 15 invited seminars and colloquia.

The following is a list of papers, organized by research area, and a selected sample of talks.

Papers

Black hole microstates

1. S. Carlip, "Effective Conformal Descriptions of Black Hole Entropy: A Review," *AIP Conf. Proc.* **1483** (2012) 54, arXiv:1207.1488.
2. S. Carlip, "Effective Conformal Descriptions of Black Hole Entropy," *Entropy* **13** (2011) 1355, arXiv:1107.2678 (solicited article).
3. S. Carlip, "Extremal and nonextremal Kerr/CFT correspondences," *JHEP* **04** (2011) 076; erratum *JHEP* **01** (2012) 008, arXiv:1101.5136.

Lattice quantum gravity

1. C. Anderson, S. Carlip, J. H. Cooperman, P. Hořava, R. Kommu, and P. R. Zulkowski, "Quantizing Horava-Lifshitz Gravity via Causal Dynamical Triangulations," *Phys. Rev.* **D85** (2012) 044027, arXiv:1111.6634.
2. M. K. Sachs, "Testing Lattice Quantum Gravity in 2+1 Dimensions," arXiv:1110.6880.

3. R. Kommu, "A Validation of Causal Dynamical Triangulations," *Class. Quant. Grav.* **29** (2012) 105003, arXiv:1110.6875.

Small scale structure

1. S. Carlip, "Spontaneous Dimensional Reduction?" *AIP Conf. Proc.* **1483** (2012) 63, arXiv:1207.4503.
2. S. Carlip and D. Grumiller, "Lower Bound on the Spectral Dimension Near a Black Hole," *Phys. Rev.* **D84** (2011) 084029, arXiv:1108.4686.
3. S. Carlip, R. A. Mosna, and J. P. M. Pitelli, "Vacuum Fluctuations and the Small Scale Structure of Spacetime," *Phys. Rev. Lett.* **107** (2011) 021303, arXiv:1103.5993.
4. S. Carlip, "The Small Scale Structure of Spacetime," in *Foundations of Space and Time*, ed. G. Ellis, J. Murugan, and A. Weltman (Cambridge University Press, 2012), arXiv:1009.1136.
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2. C. Cunliff, "Topologically Massive Gravity from the Outside In," *Class. Quant. Grav.* **28** (2011) 195024, arXiv:1012.2180.
3. S. Carlip, "Chiral Topologically Massive Gravity and Extremal B-F Scalars," *JHEP* **09** (2009) 083, arXiv:0906.2384.

Shape dynamics

1. H. Gomes, "Breaking the Uniqueness of the Shape Dynamics Hamiltonian," arXiv:1201.3969.
2. H. Gomes, "The Coupling of Shape Dynamics to Matter," in *L*oops '11, *J. Phys. Conf. Series* **360** (2012) 012058, arXiv:1112.0374.
3. H. Gomes and T. Koslowski, "Coupling Shape Dynamics to Matter Gives Spacetime," *Gen. Rel. Grav.* **44** (2012), arXiv:1110.3837.

Other work

1. S. Carlip, "Challenges for Emergent Gravity," soicited article, *Stud. Hist. Phil. Mod. Phys.*, arXiv:1207.2504.
2. C. Cunliff, "Conformal Fluctuations Do Not Establish a Minimum Length," *Class. Quant. Grav.* **29** (2012) 207001, arXiv:1201.2247.
3. C.-Y. Lin, "Emergence of General Relativity from Loop Quantum Gravity: A Summary," *Class. Quant. Grav.* **29** (2012) 082001, arXiv:1111.2107.
4. C.-Y. Lin, "Emergence of Loop Quantum Cosmology from Loop Quantum Gravity: Lowest Order in h," arXiv:1111.1766.
5. J. Cooperman, "Rescuing the Born Rule for Quantum Cosmology," *JCAP* **2** (2011) 14, arXiv:1010.3395.
6. M. Afshar, "Quasilocal Energy in FRW Cosmology," *Class. Quant. Grav.* **26** (2009) 225005, arXiv:0903.3982.

Selected talks

1. S. Carlip, "Effective Conformal Descriptions of Black Hole Entropy," Quantum Aspects of Black Holes, CQUeST, Seoul, Korea, January 2013.
2. S. Carlip, "Two-dimensional Conformal Symmetry of Short Distance Spacetime?" The Conformal Nature of the Universe, Perimeter Institute, Waterloo, Ontario, May 2012.
3. S. Carlip, "Effective Conformal Descriptions of Black Hole Entropy," Sixth International School on Field Theory and Gravitation, Petropolis, Brazil, April 2012.
4. S. Carlip, "Pitfalls for Emergent Gravity: An Outsider's View," ESF Exploratory Workshop on Gravity as Thermodynamics, Trieste, Italy, September 2011.
5. S. Carlip, "Vacuum Fluctuations and the Raychaudhuri Equation," Peyresq 16 Physics Conference, Peyresq, France, June 2011.
6. S. Carlip, "Can Atomic and Molecular Interferometry Tell Us Something about Quantum Gravity?" Fundamental Physics of Charged and Heavy Particle Interferometry Workshop, ITAMP, Cambridge, MA, April 2010.
7. S. Carlip, "Chiral Topologically Massive Gravity and the B-F Bound," Erwin Schrödinger Institute Workshop on Three-Dimensional Gravity, Vienna, Austria, April 2009.
8. H. Gomes, "Gauge/gravity holography for non-asymptotically AdS spacetimes using Shape Dynamics," 13th Marcel Grossmann Meeting, Stockholm, Sweden, July 2012.
9. H. Gomes, "The Theory of Shape Dynamics," The Conformal Nature of the Universe, Perimeter Institute, Waterloo, Ontario, May 2012.
10. M. Afshar, "Quasilocal Energy in FRW Cosmology," APS California Section Meeting, Monterrey, CA, November 2009 (winner, Kennedy Reed Award, best student theoretical research).
11. J. Cooperman, "Quantizing Hořava-Lifshitz Gravity *via* Causal Dynamical Triangulations," Workshop on Novel Numerical Methods in Quantum Field Theory and Quantum Gravity, KITP, Santa Barbara, February 2012.
12. J. Cooperman, "Causal Dynamical Triangulations: How to Simulate Quantum Gravity on Your Laptop," colloquium, Williams College, September 2011.
13. C. Cunliff, "Non-Einstein AdS_3 Asymptotics in New Massive Gravity, 28th Pacific Coast Gravity Meeting, Santa Barbara, March 2012.
14. R. Kommu, "Causal Dynamical Triangulations," APS April Meeting, Denver, CO, May 2009.
15. C.-Y. Lin, "Emergence of General Relativity from Loop Quantum Gravity," CPT de Luminy, Marseilles, France, and Institute for Theoretical Physics III, Erlangen, Germany, June 2011.

2.2 Task B1: Phenomenology and Model Building

With the advent of LHC data taking, model building and phenomenology have entered a new era in which we finally have guidance from experiment. The salient features of the LHC data are quite clear. First, there is strong evidence for a Higgs boson of some variety with mass near 125 GeV. Current data leaves open the possibility that this Higgs boson is not entirely SM-like, having in particular larger than SM rates for the diphoton final state. At the same time there is no sign of other types of new physics at mass scales below a TeV. In particular, if supersymmetry is nature's choice if it is at mass scales below a TeV it must be hidden by virtue of limited mass splittings between supersymmetric particles or else the primary strongly produced particles, such as the gluino and most squarks, must be significantly heavier than a TeV. There remains the possibility that the stop squarks are lighter as would be consistent with avoiding large fine-tuning for the Higgs mass. Similar restrictions apply to other models such as technicolor, little-Higgs and so forth. Thus, our phenomenological and model-building efforts are becoming increasingly focused on special cases and particular models. The Davis group is very active in this kind of effort with many interesting recent results and contributions. Our graduate students and postdocs are having a big impact on our research productivity.

2.2.1 Phenomenology Personnel

We list here the people involved in the UC Davis phenomenology group during the January, 2010 to April, 2013 period:

Faculty
Hsin-Chia Cheng, John F. Gunion, Markus Luty, John Terning
Postdocs:
Daniel Phalen (went to finance), Spencer Chang (faculty, Oregon U.), Giacomo Cacciapaglia (faculty, IPN Lyon), Guido Marandella (went to finance), Zhenyu Han (postdoc, Harvard U.) , Bob McElrath (working at Heidelberg U.), Annibal Medina (postdoc at Melbourne U.), Guiyu Huang (postdoc at Kansas U.), Jason Gallicchio (supervisor Antartic research base), Yuhsin Tsai (current postdoc)
Current Graduate students:
Kevin Cleary (Luty), Kit Colwell (Terning), Ralph Edezhath (Luty), Jiayin Gu (Cheng), Rachel Houtz (Terning), Jeff Hutchinson (Luty), Yun Jiang (Gunion), John McRaven (Terning), Valentina Prilepina (Luty).
Recent Former Graduate students:
Haiying Cai (postdoc at Peking U.), Yi Cai (postdoc at Jiao Tong U. Shanghai), Jared Evans (postdoc at Rutgers U.), Jamison Galloway (postdoc at U. of Rome, “La Sapienza”), David Stancato (instructor at Lone Star College).

2.3 Cheng

2.3.1 Background

Large Hadron Collider (LHC) has discovered a Higgs boson around 125–126 GeV in the first run and is currently being upgraded for its next run at the full designed center-of-mass energy. In addition to the mission of discovering the Higgs boson, it also looks for new physics at the TeV scale, which will continue in the next run. There have also been many ongoing experiments trying to detect dark matter directly or indirectly. These experiments have reached the interesting region in the weakly interacting massive particle (WIMP) dark matter scenario and will continue to cover most of the interesting parameter region in the near future. My research has been closely related to the new physics which are probed by the LHC and various dark matter experiments.

2.3.2 Research Summary (Jan. 2010 – Apr. 2013)

- **Searching and identifying new physics with missing energy signals at the LHC:** New physics scenarios with missing energy signals are very well motivated at TeV-scale colliders. They arise in most models containing a WIMP dark matter where the produced dark matter particles escape the detector, including the most popular supersymmetric extensions of the standard model. It is important to design effective search strategies and kinematic variables for new physics events with missing transverse energies at the LHC. A variable which is very useful for events with two symmetric decay chains ending in missing particles is the stransverse variable M_{T2},[16]. The original definition of M_{T2} is somewhat mysterious and opaque. Zhenyu Han and I showed that M_{T2} has a nice physical interpretation which corresponds to the minimal mother particle mass in the decay chain which is compatible with the kinematic constraints of the decay topology for a given daughter particle mass.[17] This interpretation allows natural generalizations to other event topologies and asymmetric decay chains. One can find new variables based on either signal or background topologies which can be used to identify signals or to reject backgrounds. Together with Yang Bai, Jason Gallicchio and Jiayin Gu, I identified several new variables which can be used to suppress the main $t\bar{t}$ backgrounds for the direct stop (or in general top partner) search in the semi-leptonic channel[18] and di-leptonic channel.[19] Our new variables have been adopted by both ATLAS and CMS experiments to improve the reach of stop searches.[20][21]

If new physics events with large missing transverse energies are discovered, to identify the underlying theory is still nontrivial. There are many new models which can give rise to similar collider signals. Due to the missing momentum information carried by the missing particles, the event kinematics can not be reconstructed on an event-by-event basis. In the past few years, I have been engaged in a program which attempts to identify the underlying physics if some new physics is discovered. We have constructed kinematic variables to distinguish different event topologies which have same final states.[22] With the known signal event topology, we can then use the full kinematic information of that topology to determine the masses of the invisible particles in the decay chains or even reconstruct the full event kinematics.[23] With the full kinematic information, we can further examine the angular distributions of the production and decays to determine spins of the particles involved,[24] thereby identify the physics responsible for the collider signals.

- **New physics models at the TeV scale:**
  I have continued in constructing possible new physics models at the TeV scale. Recently I have been exploring models which can give rise to non-traditional signals. For example, with Haiying Cai, Anibal Medina and John Terning, I discussed a scenario where the supersymmetric standard model couples to a strongly coupled conformal sector.[25] There is no particle in a conformal theory and the spectral density is continuous. By mixing with the conformal degrees of freedom, the superpartners of the standard model particles can also become part of the continuum spectrum. Once produced, the continuum states tend to go through cascade decays with many small steps, emitting soft visible particles. The events

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[17] H. -C. Cheng and Z. Han, JHEP **0812**, 063 (2008) [arXiv:0810.5178 [hep-ph]].
[18] Y. Bai, H. -C. Cheng, J. Gallicchio and J. Gu, JHEP **1207**, 110 (2012) [arXiv:1203.4813 [hep-ph]].
[19] Y. Bai, H. -C. Cheng, J. Gallicchio and J. Gu, arXiv:1304.3148 [hep-ph]
[20] [ATLAS Collaboration], ATLAS-CONF-2012-166, ATLAS-CONF-2013-037.
[21] [CMS Collaboration], CMS-PAS-SUS-13-011.
[22] Y. Bai and H. -C. Cheng, JHEP **1106**, 021 (2011) [arXiv:1012.1863 [hep-ph]].
[23] H. -C. Cheng, D. Engelhardt, J. F. Gunion, Z. Han and B. McElrath, Phys. Rev. Lett. **100**, 252001 (2008) [arXiv:0802.4290 [hep-ph]]; H. -C. Cheng, J. F. Gunion, Z. Han and B. McElrath, Phys. Rev. D **80**, 035020 (2009) [arXiv:0905.1344 [hep-ph]]; H. -C. Cheng and J. Gu, JHEP **1110**, 094 (2011) [arXiv:1109.3471 [hep-ph]].
[24] H. -C. Cheng, Z. Han, I. -W. Kim and L. -T. Wang, JHEP **1011**, 122 (2010) [arXiv:1008.0405 [hep-ph]].
[25] H. Cai, H. -C. Cheng, A. D. Medina and J. Terning, Phys. Rev. D **80**, 115009 (2009) [arXiv:0910.3925 [hep-ph]]; H. Cai, H. -C. Cheng, A. D. Medina and J. Terning, Phys. Rev. D **85**, 015019 (2012) [arXiv:1108.3574 [hep-ph]].

typically have high multiplicities with soft visible particles and spherical shape, which reflect the conformal nature of the underlying theory. Such signals are quite challenging at colliders. More sophisticated triggers and search strategies are needed to identify them.

- **Dark matter interpretation in astrophysical observations:**
  Dark matter may be detected directly in direct detection experiments, or indirectly from astrophysical observations. In recent years, there have been several experiments observing excesses of electrons/positrons in the cosmic ray data above the expected backgrounds. In particular, PAMELA saw the $e^+/(e^+ + e^-)$ ratio rises with energies up to ~ 100 GeV, which indicates new sources of high energy positrons.[26] This observation has been confirmed by both Fermi-LAT[27] and AMS-02,[28] and extended to ~ 350 GeV. In addition, Fermi-LAT also observed hardening of the total $e^+ + e^-$ spectrum around $300 \sim 500$ GeV, above the expected background spectrum.[29] They could be a sign of the dark matter, due to either the dark matter annihilation in the galactic halo or the decaying dark matter. However, most dark matter models which attempt to explain these observations are in conflict or in strong tension with the diffuse gamma ray constraints

  With W. C. Huang, I. Low, A. Menon, and G. Shaughnessy, I have proposed a new scenario where the dark matter particles go through three-body decays, producing a pair of standard model particles and another stable missing particle.[30] The long lifetime can be realized naturally in the goldstini scenario. If supersymmetry (SUSY) is spontaneously broken in multiple sequestered sectors, there will be a corresponding goldstino in each SUSY breaking breaking sector. One linear combination is eaten and becomes the longitudinal mode of the gravitino. The other will acquire a mass twice the gravitino mass due to the supergravity effect at the lowest order. If the gravitino and an uneaten goldstino are the lightest and next lightest supersymmetric particles, the goldstino will have a long lifetime and can be the dark matter particle. It decays to gravitino plus a pair of standard model particles through dimension-8 operators, and with suitable SUSY breaking parameters, can naturally have a lifetime required for the flux to account for the excesses observed by PAMELA, Fermi-LAT and AMS-02. Due to the missing particle (gravitino), the standard model particles from the dark matter decay have a smooth and softer spectrum. As a result, it can fit both the positron excess observed by PAMELA, Fermi-LAT and AMS-02, and the hardening feature of the total electron+positron spectrum in Fermi-LAT data well with universal couplings to all three lepton flavors. It can also safely satisfy the cosmic gamma-ray constraints. The decaying dark matter with three-body decays is one of the few remaining attractive possibilities If the excesses observed in PAMELA and Fermi-LAT are indeed due to dark matter.

Publications (Jan. 2010 – Apr. 2013)

- H.-C. Cheng, "2009 TASI Lecture – Introduction to Extra Dimensions," arXiv:1003.1162 [hep-ph].
- H. -C. Cheng, "Continuum Superpartners," Int. J. Mod. Phys. A **25**, 5210 (2010) [arXiv:1003.1163 [hep-ph]].

[26] O. Adriani *et al.* [PAMELA Collaboration], Nature **458**, 607 (2009) [arXiv:0810.4995 [astro-ph]].
[27] M. Ackermann *et al.* [Fermi LAT Collaboration], Phys. Rev. Lett. **108**, 011103 (2012).
[28] M. Aguilar *et al.* [AMS Collaboration] Phys. Rev. Lett. **110**, no. 14, 141102 (2013)
[29] A. A. Abdo *et al.* [Fermi LAT Collaboration], Phys. Rev. Lett. **102**, 181101 (2009).
[30] H. -C. Cheng, W. -C. Huang, I. Low and A. Menon, JHEP **1103**, 019 (2011) [arXiv:1012.5300 [hep-ph]]; H. - C. Cheng, W. -C. Huang, I. Low and G. Shaughnessy, JCAP **1301**, 033 (2013) [arXiv:1205.5270 [hep-ph]].

- H. -C. Cheng, Z. Han, I. -W. Kim and L. -T. Wang, "Missing Momentum Reconstruction and Spin Measurements at Hadron Colliders," JHEP **1011**, 122 (2010) [arXiv:1008.0405 [hep-ph]].
- Y. Bai and H. -C. Cheng, "Identifying Dark Matter Event Topologies at the LHC," JHEP **1106**, 021 (2011) [arXiv:1012.1863 [hep-ph]].
- H. -C. Cheng, W. -C. Huang, I. Low and A. Menon, "Goldstini as the decaying dark matter," JHEP **1103**, 019 (2011) [arXiv:1012.5300 [hep-ph]].
- D. Alves *et al.* [LHC New Physics Working Group Collaboration], "Simplified Models for LHC New Physics Searches," arXiv:1105.2838 [hep-ph].
- H. Cai, H. -C. Cheng, A. D. Medina and J. Terning, "SUSY Hidden in the Continuum," Phys. Rev. D **85**, 015019 (2012) [arXiv:1108.3574 [hep-ph]].
- H. -C. Cheng and J. Gu, "Measuring Invisible Particle Masses Using a Single Short Decay Chain," JHEP **1110**, 094 (2011) [arXiv:1109.3471 [hep-ph]].
- Y. Bai, H. -C. Cheng, J. Gallicchio and J. Gu, "Stop the Top Background of the Stop Search," JHEP **1207**, 110 (2012) [arXiv:1203.4813 [hep-ph]].
- H. -C. Cheng, W. -C. Huang, I. Low and G. Shaughnessy, "The case for three-body decaying dark matter," JCAP **1301**, 033 (2013) [arXiv:1205.5270 [hep-ph]].
- Y. Bai, H. -C. Cheng, J. Gallicchio and J. Gu, "A Toolkit of the Stop Search via the Chargino Decay," arXiv:1304.3148 [hep-ph].

Conference talks (Jan. 2010 – Apr. 2013)

- "Disentangling New Physics with Missing Energy at the LHC,"
  NCTS LHC Topical Program, 2nd Workshop, National Center for Theoretical Sciences, Hsinchu, Taiwan, Dec. 8–10, 2010.
- "Measuring invisible particle masses at hadron colliders,"
  The Ninth Particle Physics Phenomenology Workshop (PPP9), National Central University, Chungli, Taiwan, June 3–6, 2011.
- "Measuring invisible particle masses using a single short decay chain,"
  TH-LPCC Summer Institute on LHC Physics (THLPCC11), CERN, Geneva, Switzerland, Aug. 01 – Sep. 02, 2011.
- "Kinematic techniques for missing energy events at hadron colliders,"
  The 19th International Conference on Supersymmery and Unification of Fundamental Interactions (SUSY 2011), Fermilab, Batavia, Illinois, USA, Aug. 28 – Sep. 02, 2011.
- "Kinematic considerations for events with missing particles,"
  Preworkshop on Very Heavy Quark at the LHC, National Taiwan University, Dec. 20–21, 2011.
- "Third generation squark searches with new Kinematic variables,"
  The 20th International Conference on Supersymmery and Unification of Fundamental Interactions (SUSY 2012), Peking University, Beijing, China, Aug. 13 –18, 2012.

Seminars (Jan. 2010 – Apr. 2013)

- “Spin determination from kinematic reconstruction at the LHC,”
National Taiwan University, Taipei, Taiwan, July 14, 2010.

- “Spin determination from kinematic reconstruction at the LHC,”
National Center for Theoretical Sciences, Hsinchu, Taiwan, July 15, 2010.

- “Invisible particle mass determination at hadron colliders,”
Fermilab, Batavia, Illinois, Aug. 26, 2010.

- “Spin determination from kinematic reconstruction at the LHC,”
University of Maryland, College Park, Maryland, Aug. 30, 2010.

- “Identifying missing energy event topologies at the LHC,”
Harvard University, Cambridge, Massachusetts, Apr. 26, 2011.

- “A supersymmetric candidate for decaying dark matter,”
Academia Sinica, Taipei, Taiwan, May 27, 2011.

- “Kinematic variables for events with missing particles,”
SLAC National Accelerator Laboratory, Mar. 23, 2012.

- “Kinematic variables for events with missing particles,”
Argonne National Laboratory, Illinois, Apr. 17, 2012.

- “Kinematic variables for events with missing particles,”
Princeton University, New Jersey, Apr. 30, 2012.

- “Kinematic variables for events with missing particles,”
National Center for Theoretical Sciences, Hsinchu, Taiwan, June 12, 2012.

- “Kinematic variables for events with missing particles,”
Academia Sinica, Taipei, Taiwan, June 13, 2012.

- “Kinematic variables for events with missing particles,”
National Taiwan University, Taipei, Taiwan, Sep. 10, 2012.

- “Heavy-light mesons in AdS/QCD,”
Academia Sinica, Taipei, Taiwan, Dec. 28, 2012.

Workshops participated (Jan. 2010 – Apr. 2013)

- UC Davis HEFTI Workshop “Light Dark Matter,” University of California, Davis, Apr. 30 – May 1, 2010.

- West Coast LHC Theory Network Meeting, University of California, Santa Cruz, May 21, 2010.

- Workshop on Topologies for Early LHC Searches, SLAC National Accelerator Laboratory, Menlo Park, California, Sep. 22–25. 2010.

- NCTS LHC Topical Program, 2nd Workshop, National Center for Theoretical Sciences, Hsinchu, Taiwan, Dec. 8–10, 2010.

- UC Davis HEFTI Workshop “Bubbles in the Sky,” University of California, Davis, Apr. 1–2, 2011.

- UC Davis HEFTI Workshop "The Tau Portal," University of California, Davis, Apr. 7, 2011.
- UC Davis HEFTI Workshop "SUSY Recast," University of California, Davis, Apr. 8–9, 2011.
- The Ninth Particle Physics Phenomenology Workshop (PPP9), National Central University, Chungli, Taiwan, June 3–6, 2011.
- KITP Workshop "The First Year of the LHC," The Kavli Institute for Theoretical Physics, University of California, Santa Barbara, June 13 – July 1, 2011.
- TH-LPCC Summer Institute on LHC Physics (THLPCC11), CERN, Geneva, Switzerland, Aug. 15–26, 2011.
- UC Davis HEFTI Workshop "Hidden SUSY," University of California, Davis, Nov. 8–9, 2011.
- Preworkshop on Very Heavy Quark at the LHC, National Taiwan University, Taipei, Taiwan, Dec. 20–21, 2011.
- PCTS Workshop: Hot Topic at Colliders: Exploring Hints of New Physics, Princeton Center for Theoretical Science, Princeton University, Princeton, New Jersey, Apr. 27–29, 2012.
- Aspen Workshop "The LHC Shows the Way," Aspen Center for Theoretical Physics, Aspen, Colorado, Jul. 22–Aug. 5, 2012.
- Haber-Dine Symposium "The Search for Fundamental Physics: Higgs Bosons & Supersymmetry," University of California, Santa Cruz, Jan. 4–6, 2013
- UC Davis HEFTI Workshop "The LHC Higgs Signal: Characterization, Interpretation and BSM Model Implications," University of California, Davis, Apr. 22–26, 2013.
- KITP Workshop "LHC–The First Part of the Journey," The Kavli Institute for Theoretical Physics, University of California, Santa Barbara, Apr. 28 – May 18, 2013.

2.4 Gunion

2.4.1 Background and Highlights for January, 2010 through April 2013

Theoretical phenomenological high energy physics has now entered a new era following the 7 and 8 TeV runs. The LHC has observed a Higgs boson-like signal, which has been the focus of Gunion's most recent work, which includes characterizing the nature of the boson in terms of best fits to its quark and vector boson couplings. The LHC does not (yet) see signs of other new physics (such as supersymmetric particles) and this places strong and important constraints on models such as the Minimal Supersymmetric Model (MSSM) and the Next-to-Minimal Supersymmetric Model (NMSSM). Gunion has, in particular, explored how the NMSSM can be simultaneously consistent with the Higgs boson signal at 125 GeV, the current LHC limits for supersymmetric particle masses, and naturalness. In fact, the NMSSM seems to be the "last man standing" for a simple supersymmetric model capable of consistency with all three. The possibly non-standard level of the LHC Higgs-like signals at 125 GeV and the possible presence of additional Higgs-like signals at other masses has also motivated Gunion to consider (again) the Randall-Sundrum model of a warped 5th dimension with Higgs-radion mixing. This model can, in fact, provide a fit to the observations and, of course, the RS model itself is a nice alternative to the supersymmetric approach to naturalness (explaining the large hierarchy between the TeV scale and the Planck scale). But, it too is becoming increasingly constrained by the failure to observe any KK excitations. In the more general context of LHC results, as the LHC continues operation there will be increased pressure to analyze and present results in the most efficient manners possible. Gunion has co-authored a number of reports related to these issues.

- **CMS collaboration papers:**

  Gunion participated in and is co-author of three CMS papers. The first is a search [11] for $gg \to a_1 \to \mu^+\mu^-$, where the a_1 is the lightest of two NMSSM (see below) CP-odd Higgs bosons. The relevance of such a search was originally pointed out by Gunion and Dermisek [26]. This paper greatly improves limits on such a light a_1 for $m_{a_1} > 6 - 7$ GeV (depending on $\tan\beta$) and indeed provides the only limits in the region $m_{a_1} > M_\Upsilon$.

  Gunion is also co-author of the main Higgs search paper by CMS [9] as well as the associated general Science article [2]. In this regard, it should be recalled that Gunion was the first to suggest and establish the viability of light Higgs discovery in the di-photon and $ZZ^* \to 4\ell$ final states in two papers with various collaborators. [31] This crucial contribution is finally receiving some recognition. The benchmark studies performed provided crucial input to detector designs, most particularly the need for a very high resolution electromagnetic calorimeter.

  Gunion is also one of the primary authors of the pMSSM (phenomenological MSSM) CMS analysis of the 7 TeV data set, CMS PAS SUS-12-030. While not a publication, this analysis is public and is proving quite influential about future analyses of the 8 TeV data set (now in progress, with Gunion continuing a prominent role) and establishes where the weaknesses of current analyses limiting supersymmetric particles lie.

- **NMSSM:**

  Before the LHC era, Gunion developed (in collaboration with R. Dermisek) the first model in which the Higgs boson could have been light (even below the nominal LEP limit) but unobserved by virtue of exotic decays.[32] In the context of the NMSSM, the key (very difficult to detect) decay is $h \to aa$, with $m_a < 2m_b$ implying $a \to \tau\tau$. Here, the h is the lightest CP-even Higgs boson and typically SM-like. The a is the light, mainly singlet, CP-odd Higgs boson and a very light mass value is protected by a $U(1)_R$ symmetry of the NMSSM. Pre-LHC papers [25][26] on this idea focused on testing/constraining this approach including a means for searching for the light a using its rare decays to two muons. This latter approach was pursued by Gunion and CMS collaborators and new limits appeared in an official CMS paper [11] with Gunion and Max Chertok from U.C. Davis as primary authors. Of course, with the discovery of a fairly SM-like Higgs boson at 125 GeV the original picture in which $h \to aa$ decays are dominant is no longer needed to hide the Higgs, but such decays can in fact still be present with a branching ratio of as much as 30% (see later discussion on Higgs fitting) and must certainly be searched for (work in progress within CMS collaboration, Gunion, Cherok et.al.). More generally, a light a remains very possible in the NMSSM and searching for it, and placing limits on it, remains important.

  The NMSSM can also allow for very light dark matter, the key ingredients being the multiple Higgs bosons of the NMSSM, especially the light a. Such light dark matter, explored early on

[31] J. F. Gunion, P. Kalyniak, M. Soldate and P. Galison, "Searching For The Intermediate Mass Higgs Boson," Phys. Rev. D **34**, 101 (1986). J. F. Gunion, G. L. Kane and J. Wudka, "Search Techniques for Charged and Neutral Intermediate Mass Higgs Bosons," Nucl. Phys. B **299**, 231 (1988).

[32] R. Dermisek and J. F. Gunion, "Escaping the large fine tuning and little hierarchy problems in the next to minimal supersymmetric model and $h \to aa$ decays," Phys. Rev. Lett. **95**, 041801 (2005) [hep-ph/0502105].

by Gunion, Hooper and McElrath, [33] would be consistent with observations of Cogent, DAMA and other experiments. Although these observational hints remain controversial in the light of limits from other experiments, in particular Xenon100, in a series of papers [20], [21], [22] Gunion and collaborators have demonstrated the NMSSM models that could explain the light dark matter hints. The relevant portion of NMSSM parameter space is being increasingly constrained by LHC data but there is still room. As more data becomes available it will be important to continually update the situation.

Of course, all theoretical models must be reassessed in light of the LHC discovery of a SM-like Higgs boson with mass near 125 GeV. In the context of supersymmetry, such a high mass is much more naturally accommodated in the NMSSM context than in the minimal MSSM. In [15], a sequel to [20], Gunion, Kraml and Jiang (Gunion's student) explored whether the constrained (universal GUT scale boundary conditions or slight generalizations thereof) NMSSM could explain the 125 GeV Higgs-like signals while remaining consistent with all other constraints, including those from B-physics, the WMAP dark matter window, and, most particularly, the muon anomalous magnetic moment. We found that consistency was possible, but that achieving such consistency required that the observed Higgs be the lightest NMSSM CP-even Higgs h_1 and that the h_1 should be very SM-like. Further, the allowed portion of parameter space is such that gluinos and 1st and 2nd generation squarks should have masses well above a TeV, while the stop could still have mass of order 500 GeV. Of particular note is the fact that a reasonable value of a_μ does not allow for the LHC Higgs signals (e.g. in the $\gamma\gamma$ mode and the 4ℓ mode) to be enhanced relative to the SM. Early data suggested that the $\gamma\gamma$ mode could be enhanced. However, the final data (especially CMS data) is consistent with absence of signal enhancements and so the constrained model could be consistent with both Higgs data and a_μ.

Relaxing the muon anomalous magnetic moment constraint (as considered appropriate by many) opens a vast array of possibilities. We have explored these in three papers showing that enhanced diphoton rates for one Higgs at 125 GeV are almost generic when the h_1 and h_2 of the NMSSM are not too far apart in mass. In [10] we explore the case where they are quite close in mass, possibly degenerate within experimental mass resolution. In [8] we develop diagnostic tools that would definitively signal the presence of two nearly degenerate Higgs bosons. These tools have very general applicability beyond the NMSSM. In [7] we show that NMSSM scenarios can be constructed in which the two lightest Higgs bosons have masses of 125 GeV and 136 GeV and have properties consistent with the LHC signals at 125 GeV seen by ATLAS and CMS, the CMS excesses above background (especially the diphoton excess) at 136 GeV, and the Tevatron excess in the Vh channel with $h \to b\bar{b}$ which is most consistent with a h mass above 130 GeV as opposed to 125 GeV. In [6] we explored another interesting scenario in which the light h_1 has mass of $\sim$ 98 GeV and explains the old LEP excess in $Z^* \to Zb\bar{b}$ at $M_{b\bar{b}} = 98$ GeV, while the h_2 has mass $\sim$ 125 GeV and gives a signal compatible with the LHC Higgs data. Scenarios of this type are easy to find and lead to many correlated expectations for other SUSY and Higgs observables.

- **General Two-Higgs Doublet Model**

  In a highly-cited paper [5], I and collaborators explored the consistency of two-Higgs-doublet models (2HDM) with the observed LHC signal at $\sim$ 125 GeV. We considered cases where it is the lighter h that has mass of $\sim$ 125 GeV as well as when it is the heavier H that has

[33] J. F. Gunion, D. Hooper and B. McElrath, "Light neutralino dark matter in the NMSSM," Phys. Rev. D **73**, 015011 (2006) [hep-ph/0509024].

mass of ~ 125 GeV. We also considered the possibilities of h-H, h-A and H-A degeneracies, delineating, in particular, the various types of rate enhancements that might result in various channels.

- **Randall-Sundrum Higgs**

  As noted in the introduction, the Randall-Sundrum warped 5th dimension model[34] is an attractive alternative to supersymmetry for explaining the hierarchy between the TeV and Planck mass scales. It has a rich Higgs phenomenology. In the simplest RS model there is one "bare" (SM-like) Higgs boson that could naturally be light. In addition, the RS model predicts the existence of the radion, which is a very Higgs-like object with naturally enhanced $\gamma\gamma$ and gg couplings. Further, the radion and Higgs, having the same quantum numbers, can mix,[35] leading to a rich phenomenology involving 2 Higgs-like states, denoted h and ϕ.[36] In [14], Grzadkowski, Gunion and Toharia explored the extent to which the RS model could describe the LHC data, in particular we examined whether the $\gamma\gamma$ signal at 125 GeV could be enhanced relative to the SM as well as the possible presence of a 2nd Higgs signal as seen in current CMS data at 136 GeV (with enhanced $\gamma\gamma$ rate). We find that with appropriate model and mixing choices, these two signals can be obtained in the RS context.

- **Simplified Models**

  In [19] a large group of theorists and experimentalists summarized the results of a series of meetings in which a large range of "simplified" models for new physics at the LHC are categorized and summarized. Our goal was to address two principal questions with regard to early LHC searches. The first is whether certain classes of new physics can evade the existing ATLAS and CMS search programs, but still be detectable with new search techniques or optimization strategies. Second, it is important to understand the physical implications of new-physics searches, whether they see evidence for new physics or constrain it. We proposed that very simple models of new physics, involving relatively few particles and decay modes, offer a natural framework for both tasks. Our expectation was that ATLAS and CMS can enhance the applicability of new-physics searches by considering their sensitivity to such simplified models. For example, in supersymmetry it is possible that the most important observational channel could be gluino pair production followed by each gluino decaying almost entirely in one of 3 ways: $\tilde{g} \to q\bar{q}\chi^0$; $\tilde{g} \to \chi^\pm + q\bar{q}$ with $\chi^\pm \to W^\pm\chi^0$; or $\tilde{g} \to {\chi'}^0 + q\bar{q}$ with ${\chi'}^0 \to Z\chi^0$. ATLAS and CMS have adopted these ideas and the various simplified models we proposed and the results are quite revealing in terms of how discovery potential depends upon the masses of the particles involved and the complexity of the decay chains.

- **Benchmark Models**

  Benchmark models provide another approach to evaluating the relevance of LHC results and establishing where new physics might be "hiding". In [16], a follow-on effort from [13], a group of theorists examined their favorite Beyond the SM (BSM), mainly supersymmetric, model classes looking for scenarios that might prove particularly challenging for LHC discovery. High

[34] L. Randall and R. Sundrum, "A Large mass hierarchy from a small extra dimension," Phys. Rev. Lett. **83**, 3370 (1999) [hep-ph/9905221].

[35] G. F. Giudice, R. Rattazzi and J. D. Wells, "Graviscalars from higher dimensional metrics and curvature Higgs mixing," Nucl. Phys. B **595**, 250 (2001) [hep-ph/0002178].

[36] D. Dominici, B. Grzadkowski, J. F. Gunion and M. Toharia, "The Scalar sector of the Randall-Sundrum model," Nucl. Phys. B **671**, 243 (2003) [hep-ph/0206192]. J. L. Hewett and T. G. Rizzo, "Shifts in the properties of the Higgs boson from radion mixing," JHEP **0308**, 028 (2003) [hep-ph/0202155].

on the list of such models were special MSSM and NMSSM cases. Our goal was to alert the experimental community to particular situations to which they should attempt to increase their analysis sensitivity. The model situations developed in this study are of importance given the absence of excesses beyond the SM after the 7 and 8 TeV runs.

- **Recommendations for the Presentation of LHC Results**

  In a not unrelated paper [12], a group of experimentalists and theorists collaborated extensively through a series of meetings and email interactions to develop some very specific recommendations regarding how LHC results should be presented. This included recommendations on how to present limits obtained in the context of simplified models, results for Higgs signals and so forth. Recommendations included development of a fast simulation tool that is "approved" by CMS and ATLAS, publication of likelihood profiles and providing of details regarding experimental analysis procedures and similar (perhaps as appendages of extra information to a main paper within Spires).

- **The Wjj excess**

  The preprint [17] was unabashed ambulance chasing. In this paper, Gunion looked at the possibility to use an unusual part of two-Higgs-doublet parameter space (low $\tan\beta$) to obtain a Wjj signal as large as that seen at the Tevatron. This turned out to be possible but only if there were other BSM contributions to such well-known processes as $b \to s\gamma$. Gunion did not pursue publication since it was only shortly later that the LHC experiments presented data that excluded the scenario because of its predictions for other, but closely related, final states.

- **Higgs and a 4th generation**

  One of the earliest revitalizations (at the time of early LHC data) of the influence of a 4th generation on Higgs physics was [18]. In this paper, Gunion pointed out that even the then available crude limits on light Higgs boson production implied that if the Higgs was light then a 4th generation was pretty much eliminated as a possibility. Since this paper, there have been many studies of this same topic, including ones by the experimentalists themselves. A particularly interesting theoretical aspect of a 4th generation turns out to be the fact that in the MSSM (and other supersymmetric models) the lightest Higgs boson is pushed to rather high masses and that the only Higgs boson that could be at low mass is the CP-odd Higgs boson. In this paper, Gunion showed that it could give a significant $\gamma\gamma$ final state signal. Of course, the observation of the SM-like Higgs signal at ~ 125 GeV implies that there is no room left for a 4th generation without moving to much more exotic models.

- **Higgs Fitting**

  In [4] I and collaborators fit the properties of the observed ~ 125 GeV Higgs-like signal in terms of the most basic Lagrangian parameters specifying the WW, ZZ, $t\bar{t}$ and $b\bar{b}$ Higgs couplings, assuming the absence of invisible decays. Ours was the most complete analysis incorporating all the pre-2013 data from ATLAS and CMS. In the follow-up paper [3] we allowed for invisible decays and found that excellent fits to the data in the various scenarios of interest were also possible when the Higgs has a large branching fraction to either undetected (e.g. $h \to aa$) decays or invisible decays. As noted earlier, such decays can be of considerable importance in the NMSSM.

Gunion - Papers and Talks January 2010 to April 2013

Papers

1. **"Helmholtz Aliance Linear Collider Forum : Proceedings of the Workshops Hamburg, Munich, Hamburg 2010-2012, Germany"** G. Moortgat-Pick, I. Fleck, S. Riemann, F. Simon, O. S. Adeyemi, G. Alexander, M. S. Amjad and V. V. Andreev *et al.*. 10.3204/DESY − 12 − 123H
2. **"A New Boson with a Mass of 125 GeV Observed with the CMS Experiment at the Large Hadron Collider"** S. Chatrchyan *et al.* [CMS Collaboration]. 10.1126/science.1230816 Science **338**, 1569 (2012).
3. **"Status of invisible Higgs decays"** G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml. arXiv:1302.5694 [hep-ph] 10.1016/j.physletb.2013.05.024 Phys. Lett. B **723**, 340 (2013)
4. **"Higgs Couplings at the End of 2012"** G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml. arXiv:1212.5244 [hep-ph] 10.1007/JHEP02(2013)053 JHEP **1302**, 053 (2013)
5. **"Two-Higgs-Doublet Models and Enhanced Rates for a 125 GeV Higgs"** A. Drozd, B. Grzadkowski, J. F. Gunion and Y. Jiang. arXiv:1211.3580 [hep-ph] 10.1007/JHEP05(2013)072 JHEP **1305**, 072 (2013)
6. **"Higgs Bosons at 98 and 125 GeV at LEP and the LHC"** G. Belanger, U. Ellwanger, J. F. Gunion, Y. Jiang, S. Kraml and J. H. Schwarz. arXiv:1210.1976 [hep-ph] 10.1007/JHEP01(2013)069 JHEP **1301**, 069 (2013)
7. **"Two Higgs Bosons at the Tevatron and the LHC?"** G. Belanger, U. Ellwanger, J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1208.4952 [hep-ph]
8. **"Diagnosing Degenerate Higgs Bosons at 125 GeV"** J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1208.1817 [hep-ph]
9. **"Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC"** S. Chatrchyan *et al.* [CMS Collaboration]. arXiv:1207.7235 [hep-ex] Phys. Lett. B
10. **"Could two NMSSM Higgs bosons be present near 125 GeV?"** J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1207.1545 [hep-ph]
11. **"Search for a light pseudoscalar Higgs boson in the dimuon decay channel in pp collisions at sqrt(s) = 7 TeV"** S. Chatrchyan *et al.* [CMS Collaboration]. arXiv:1206.6326 [hep-ex]
12. **"Searches for New Physics: Les Houches Recommendations for the Presentation of LHC Results"** S. Kraml, B. C. Allanach, M. Mangano, H. B. Prosper, S. Sekmen, C. Balazs, A. Barr and P. Bechtle *et al.*. arXiv:1203.2489 [hep-ph] Eur. Phys. J. C **72**, 1976 (2012)
13. **"Les Houches 2011: Physics at TeV Colliders New Physics Working Group Report"** G. Brooijmans, B. Gripaios, F. Moortgat, J. Santiago, P. Skands, D. Albornoz Vasquez, B. C. Allanach and A. Alloul *et al.*. arXiv:1203.1488 [hep-ph]
14. **"Higgs-Radion interpretation of the LHC data?"** B. Grzadkowski, J. F. Gunion and M. Toharia. arXiv:1202.5017 [hep-ph] Phys. Lett. B **712**, 70 (2012)

15. **"The Constrained NMSSM and Higgs near 125 GeV"** J. F. Gunion, Y. Jiang and S. Kraml. arXiv:1201.0982 [hep-ph] Phys. Lett. B **710**, 454 (2012)
16. **"Benchmark Models, Planes, Lines and Points for Future SUSY Searches at the LHC"** S. S. AbdusSalam, B. C. Allanach, H. K. Dreiner, J. Ellis, U. Ellwanger, J. Gunion, S. Heinemeyer and M. Kraemer *et al.*. arXiv:1109.3859 [hep-ph] Eur. Phys. J. C **71**, 1835 (2011)
17. **"A two-Higgs-doublet interpretation of a small Tevatron Wjj excess"** J. F. Gunion. arXiv:1106.3308 [hep-ph]
18. **"Ruling out a 4th generation using limits on hadron collider Higgs signals"** J. F. Gunion. arXiv:1105.3965 [hep-ph]
19. **"Simplified Models for LHC New Physics Searches"** D. Alves *et al.* [LHC New Physics Working Group Collaboration]. arXiv:1105.2838 [hep-ph]
20. **"Next-to-Minimal Supersymmetric Model Higgs Scenarios for Partially Universal GUT Scale Boundary Conditions"** J. F. Gunion, D. E. Lopez-Fogliani, L. Roszkowski, R. Ruiz de Austri and T. A. Varley. arXiv:1105.1195 [hep-ph] Phys. Rev. D **84**, 055026 (2011)
21. **"The elusive Higgs boson(s)"** J. F. Gunion. Int. J. Mod. Phys. A **25**, 4163 (2010).
22. **"The Higgs Sector and CoGeNT/DAMA-Like Dark Matter in Supersymmetric Models"** J. F. Gunion. arXiv:1010.1789 [hep-ph] J. Phys. Conf. Ser. **259**, 012012 (2010)
23. **"CoGeNT, DAMA, and Neutralino Dark Matter in the Next-To-Minimal Supersymmetric Standard Model"** J. F. Gunion, A. V. Belikov and D. Hooper. arXiv:1009.2555 [hep-ph]
24. **"CoGeNT, DAMA, and Light Neutralino Dark Matter"** A. V. Belikov, J. F. Gunion, D. Hooper and T. M. P. Tait. arXiv:1009.0549 [hep-ph] Phys. Lett. B **705**, 82 (2011)
25. **"New constraints on a light CP-odd Higgs boson and related NMSSM Ideal Higgs Scenarios"** R. Dermisek and J. F. Gunion. arXiv:1002.1971 [hep-ph] Phys. Rev. D **81**, 075003 (2010)
26. **"Direct production of a light CP-odd Higgs boson at the Tevatron and LHC"** R. Dermisek and J. F. Gunion. arXiv:0911.2460 [hep-ph] Phys. Rev. D **81**, 055001 (2010)

Talks

1. Univ. Autonoma Barcelona, IFAE Colloquium, January 18, 2010: "The LHC and Beyond"
2. Invited Plenary Talk at "Quantum Mechanics, Elementary Particles, Quantum Cosmology and Complexity",
3. Singapore, February 24, 2010: "The Elusive Higgs Boson(s)" CERN Seminar, January 22, 2010: "Update on NMSSM "Ideal Higgs" Scenarios"
4. Fermilab Seminar, April 7, 2010: "Update on NMSSM "Ideal Higgs" Scenarios"
5. Plenary Talk at US CMS Meeting, Brown University, May 8, 2010: "CMS Prospects for Discovering a light CP-odd Higgs Boson and NMSSM Implications"

6. Plenary Talk at MCTP Higgs Workshop, University of Michigan, May 15, 2010: "Constraints on and Direct Discovery Prospects for the Light CP-odd Higgs Boson of NMSSM Ideal Higgs Scenarios"
7. Plenary Talk at West Coast LHC Meeting, U.C. Santa Cruz, May 21, 2010: "Direct Discovery Prospects for the Light CP-odd Higgs Boson of NMSSM Ideal Higgs Scenarios"
8. Plenary Talk at the Higgs Hunting Workshop, Orsay, July 30, 2010: "New Results for NMSSM Higgs and Dark Matter"
9. Plenary Talk at PASCOS 2010, Valencia, July 22, 2010: "New Results for NMSSM Higgs and Dark Matter"
10. SLAC Topologies Workshop, SLAC, September 22, 2010: "Higgs Signals for SUSY Models Consistent with CoGeNT/DAMA"
11. Summary of the U.C. Davis SUSY/Recast Workshop, U.C. Davis, April 8-9, 2011, presented at the LPCC conference on "Status of Higgs and BSM searches at the LHC", April 13, 2011: "Report from the "SUSY/Recast Workshop"
12. Blois Workshop, June 2, 2011: "Interpretation of Results from Direct Dark Matter Searches"
13. Saclay seminar, June 6, 2011: "Higgs in the light of Hadron Collider limits: impact on a 4th generation"
14. Muon Collider Workshop, June 28, 2011: "Physics Cases for Muon Colliders – part I"
15. Muon Collider Workshop, June 29, 2011: "Physics Cases for Muon Colliders – part II"
16. CERN, LPCC Workshop, August 23, 2011: "A two-Higgs-doublet interpretation of a small Wjj excess"
17. Scalars 2011, Warsaw, August 28, 2011: "The 2HDM at low tan beta: Wjj and gamma gamma signals as case studies"
18. Interpretation of LHC Results, TH/LPCC Workshop, September 1, 2011: "Hidden / Camouflaged Higgs"
19. Oklahoma University Seminar, October 27, 2011: "Are there Hidden Higgs Bosons?"
20. Hadron Collider Physics, November 17, 2011 "Is (are) the Higgs Boson (s) Hidden"
21. Higgs Working Groups, Orsay, November 17, 2011 "Is (are) the Higgs Boson (s) Hidden"
22. Grenoble Higgs Workshop, February 2, 2012 "Higgs-Radion Mixing the RS Model and LHC Higgs-like Excesses"
23. CMS Seminar, February 6, 2012 "Higgs-Radion Mixing and the LHC Higgs-like Excesses"
24. Linear Collider Forum, DESY, February 7, 2012 "Implications of LHC Higgs-like signals in the Randall-Sundrum Model context allowing for higgs-radion mixing"
25. CERN Theory Group, February 10, 2012 "Higgs-Radion mixing in the Randall Sundrum model and the LHC Higgs-like excesses"
26. LHC2TSP, March 27, 2012 "B(SM and MSSM) Higgs bosons consistent with LHC Hints"
27. Planck 2012, Warsaw, June 1, 2012 "Implications for BSM Higgs Bosons of LHC > SM Higgs Hints"

28. CERN Workshop on Implications of LHC results for TeV-scale physics, July 14, 2012 ”Degenerate Higgs Bosons in the NMSSM near 125 GeV”
29. CERN Theory seminar, October 16, 2012 “Multiple Higgs Model and the 125 GeV state: NMSSM and 2HDM perspectives”
30. 36th Johns Hopkins Workshop, Galileo Galilei Institute, October 17, 2012 “Multiple Higgs Models and the 125 GeV state: an NMSSM perspective”
31. University of Pittsburgh, December 4, 2012 “Multiple Higgs Models and the 125 GeV state: NMSSM and 2HDM perspectives”
32. KITP Higgs Workshop, December 20, 2013 “Multiple Higgs Models and the 125 GeV state: NMSSM and 2HDM perspectives”
33. Fundamental Physics Symposium in honor of Mike Dine and Howard Haber, January 6, 2013 “Determining the nature of the 126 GeV ‘Higgs’ signal”
34. CERN BSM Forum, January 24, 2013 “Diagnosing the nature of the 126 GeV ‘Higgs’ signal”
35. Grenoble Higgs Workshop, March 19, 2013 “Degenerate Higgs bosons at 126 GeV?”
36. Grenoble Higgs Workshop, March 21, 2013 “Triplet Higgs Scenarios”
37. Orsay, March 26, 2013 “Diagnosing the Nature of the 125-126 GeV LHC Higgs-like signal”

2.5 Luty

2.5.1 Background

My research has been divided between phenomenology and model-building motivated by the LHC, and more theoretical research. A new component of my research starting in 2011 is the theoretical investigation of 4D conformal field theories and entanglement entropy. These are related, and both subjects are experiencing a revival of interest.

2.5.2 Research Summary (Jan. 2010–Apr. 2013)

- **Minimal Composite Higgs from Minimal Conformal Technicolor:**
  Conformal technicolor is the idea that electroweak symmetry breaking can be caused by a strong conformal sector (such as QCD with many flavors) becoming strong due to a relevant perturbation (such as a fermion mass). The original motivation was that large anomalous dimensions could enhance the operators giving rise to quark and lepton masses.[37] This generated a large amount of theoretical work on the size of the allowed anomalous dimensions, which highly constrained the original motivation. As this work was beginning to appear, a group of UC Davis graduate students and I worked out the phenomenology of the simplest theory of conformal technicolor, which is simply minimal technicolor with the addition of extra techniquarks.[38] Interestingly, this model has the possibility of a composite Higgs boson. The Higgs boson was predicted to have a mass of order $\sqrt{3}m_t$, with an order-1 uncertainty due to strong coupling matrix elements. During the review period of this grant, we extended this work by constructing a complete flavor model (based on SUSY), finding that the flavor scale could not be raised above approximately 100 TeV or so.[39] It was not long after this work

[37] M. A. Luty and T. Okui, JHEP **0609**, 070 (2006).
[38] J. Galloway, J. A. Evans, M. A. Luty and R. A. Tacchi, JHEP **1010**, 086 (2010).
[39] J. A. Evans, J. Galloway, M. A. Luty and R. A. Tacchi, JHEP **1104**, 003 (2011).

was completed that the Higgs was discovered with a mass of 125 GeV. This is less than the expectation of this model, although the large theoretical uncertainty makes this unclear.

- **Quirks**
  "Quirks" are massive confined particles whose confinement scale is smaller than their mass. Such particles have very exotic phenomenology because the gauge strings connecting the particles do not break.[40] J. Evans and I collaborated with the D0 collaboration to carry out the first experimental search for quirks, manifested as highly ionizing tracks in events with missing energy.[41] J. Evans and I are collaborating with T. Knight (an experimentalist on ATLAS) to search for the full range of quirk signals at LHC. We have made significant progress since the D0 search, both clarifying the physics and constructing Monte Carlo generators for simplified models of quirk signals to define the signals and intepret the results. The work is ongoing, and expected to come out in the coming year.

- **Induced Electroweak Symmetry Breaking and Partially Composite Higgs:**
  The discovery of the 125 GeV Higgs boson has established that a light Higgs is the dominant contribution to electroweak symmetry breaking. However, in SUSY the fact that the Higgs mass is well above M_Z generally requires tuning. A new possibility for alleviating this tension is that there is an additional subleading contribution to electroweak symmetry breaking from a heavier Higgs sector. This sector need not have Yukawa couplings, and so can even be a technicolor sector. Natural models of this kind are obtained where SUSY breaking at the TeV scale induces chiral symmetry breaking and confinement in a strong conformal sector of the theory. With A. Azatov and J. Galloway I constructed explicit models of 'superconformal technicolor' and analyzed their phenomenology.[42] These models hold out the possibility of observing both supersymmetry and technicolor-like signals at the LHC. Precision electroweak corrections are suppressed compared to technicolor models, and there is no need for extended technicolor to generate fermion masses. These models also make the prediction that the Higgs self-coupling has a large suppression compared to standard model value, which can be measured at the 14 TeV LHC. In more recent work, I have extended this approach to perturbative theories. I am also pursuing the detailed LHC phenomenology of these models.

  A closely related idea is that the Higgs mixes with a composite Higgs that arises from strong dynamics at the TeV scale that is approximately supersymmetric. This was studied with R. Kitano and Y. Nakai.[43] In these models, there is generically a problem with the T parameter due to custodial symmetry breaking in the strong sector, requiring tuning of order 10%. This is still significantly less tuning than what is required in most SUSY models.

- **Extended Higgs sectors and exotic Higgs decays:**
  This has been extensively explored by many authors, but one aspect that has been less studied is heavier Higgs bosons that decay to lighter ones. This occurs mainly in models where the extended Higgs sector has stronger couplings, such as the models discussed above. Some of the possibilities were explored with S. Chang and J. Evans for the simplified models working group[44] and also in a research paper.[45] A particular example was studied with a group of

[40] J. Kang and M. A. Luty, JHEP **0911**, 065 (2009).
[41] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **105**, 211803 (2010).
[42] A. Azatov, J. Galloway and M. A. Luty, Phys. Rev. D **85**, 015018 (2012); A. Azatov, J. Galloway and M. A. Luty, Phys. Rev. Lett. **108**, 041802 (2012).
[43] R. Kitano, M. A. Luty and Y. Nakai, JHEP **1208**, 111 (2012).
[44] D. Alves *et al.* [LHC New Physics Working Group Collaboration], J. Phys. G **39**, 105005 (2012).
[45] S. Chang, J. A. Evans and M. A. Luty, Phys. Rev. D **84**, 095030 (2011).

experimentalists. [46]

With A. Pierce and D. Phalen I also studied models where Higgs decay to jets dominates.[47] The case where this decay dominates is now excluded by the Higgs discovery, but the possibility of a large branching fraction to unobserved decays such as this remains interesting.

- **4D Renormalization Group Flows:**
  The a-theorem is a long-standing conjecture in 4D conformal field theory.[48] A proof was recently given by Komargodski and Schwimmer[49] based on the idea of nonlinearly realizing conformal invariance on a nontrivial renormalization group flow that asymptotes to a conformal field theory in the UV and the IR. J. Polchinski, R. Rattazzi, and I generalized these ideas to more general renormalization group flows, proved that the UV and IR asymptotics are necessarily 4D conformal field theories under very general assumptions.[50] In particular, we showed that conformal field theory is the only possible UV or IR asymptotics that can be described in perturbation theory. For example, this rules out perturbative theories that are scale invariant but not conformal invariance. I am currently working to extend this result to give a completely non-perturbative proof that scale invariance implies conformal invariance.

- **Entanglement Entropy:**
  It has been proposed since the 1980s that black hole entropy can be accounted for by the entropy of entanglement across a black hole horizon. The latter is UV divergent, and the interpretation of this has been problematic. UC Davis graduate student Joshua Cooperman and I proposed a geometric definition of entanglement entropy that is automatically finite and compatible with the Beckenstein-Hawking area formula for the black hole entropy.[51] This also gives an unambiguous result for the subleading UV divergent terms, which are known to be related to c-theorems. The results obtained were for a special class of quantum states and entanglement boundaries, and I am continuing work on our approach to include more general situations.

Publications (Jan. 2010–Apr. 2013)

- J. H. Cooperman and M. A. Luty, arXiv:1302.1878 [hep-th].
- M. A. Luty, J. Polchinski and R. Rattazzi, JHEP **1301**, 152 (2013).
- R. Kitano, M. A. Luty and Y. Nakai, JHEP **1208**, 111 (2012).
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- A. Azatov, J. Galloway and M. A. Luty, Phys. Rev. D **85**, 015018 (2012).
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[46] J. A. Evans, B. Kilminster, M. Luty, D. Whiteson, Phys. Rev. D **85**, 055009 (2012).
[47] M. A. Luty, D. J. Phalen and A. Pierce, Phys. Rev. D **83**, 075015 (2011).
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[49] Z. Komargodski and A. Schwimmer, JHEP **1112**, 099 (2011).
[50] M. A. Luty, J. Polchinski and R. Rattazzi, JHEP **1301**, 152 (2013).
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- V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **105**, 211803 (2010).
- Y. Cai and M. A. Luty, JHEP **1012**, 037 (2010).
- J. Galloway, J. A. Evans, M. A. Luty and R. A. Tacchi, JHEP **1010**, 086 (2010).

Conference talks (Jan. 2010–Apr. 2013)

- "Asymptotics of 4D Quantum Field Theory," talk at University of Michigan (Ann Arbor) workshop on RG Flows, Entanglement, and Holography, September 17–21, 2012.
- "Asymptotics of 4D Quantum Field Theory," talk at Berkeley Center for Theoretical Physics Summit at Lake Tahoe, September 7–9, 2012.
- "Renormalization group flows in 4 dimensions," talk at Beyond the Bootstrap II workshop at Perimeter Institute, June 11–15, 2012.
- "The a-theorem and scale without conformal invariance," talk at Workshop on Strongly Coupled Physics Beyond the Standard Model, ICTP Trieste, January 25–27, 2012.
- "Superconformal technicolor," talk at The First Year of the LHC, workshop at KITP Santa Barbara, June 26–Augus 8, 2011.
- "Displaced dark matter at colliders" talk at Berkeley Center for Theoretical Physics workshop on dark matter, April 29–May 1, 2011.
- "Flavor in conformal technicolor," talk at Aspen workshop on Colliders to the Dark Sector: Understanding Dark Matter at Particle Colliders and Beyond June 20–July 18, 2010.
- "Conformal technicolor: from the weak scale to the Planck scale," plenary talk at Planck 2010, CERN, May 31–June 4, 2010.
- "Conformal technicolor: from the weak scale to the Planck scale" talk at Johns Hopkins workshop on Current Problems in Particle Theory, May 23–25 2010.

Seminars (Jan. 2010–Apr. 2013)

- "The Higgs Confronts Three Universes at the LHC," colloquium at Perimeter Institute March 13, 2013.
- "Renormalization of entanglement entropy" seminar at Perimeter Institute, March 12, 2013.
- "Renormalization of entanglement entropy" seminar at Stanford University Physics Department, March 7, 2013.
- "The Higgs Confronts Three Universes at the LHC," colloquium at UC Davis Physics Department, October 8, 2012.

- “The Higgs Confronts Three Universes at the LHC,” colloquium at Cornell University Physics Department, September 24, 2012.
- “SUSY Naturalness and Induced Electroweak Symmetry Breaking,” seminar at UC Berkeley physics department, September 11, 2012.
- “Three universes confront the LHC,” colloquium at University of Heidelberg Physics Department, May 22, 2012.
- “Three universes confront the LHC,” colloquium on Particles, Strings and the Early Universe, DESY, April 25 2012.
- “The a-theorem and the UV and IR asymptotics of quantum field theory,” seminar at DESY theory group, April 24 2012.
- “The a-theorem and the UV and IR asymptotics of quantum field theory” seminar at Institute for Theoretical Physics, University of Heidelberg, February 9 2012.
- “Superconformal technicolor,” seminar at Harvard University Physics Department, October 18, 2011.
- “Superconformal technicolor’,’ Seminar at Institute for Advanced Studies Princeton, October 17 2011.
- “Displaced dark matter at colliders” talk at Berkeley Center for Theoretical Physics workshop on dark matter, April 29–May 1, 2011.
- “Particle physics and the LHC: a tale of three universes,” MIT Labratory for Nuclear Science Colloquium, October 18, 2010.
- “Flavor in conformal technicolor,” seminar at MIT particle theory group, October 18 2010.
- “Flavor in conformal technicolor,” seminar at SLAC theory group, September 1, 2010.

Workshops participated (Jan. 2010–Apr. 2013)

- UC Davis HEFTI Workshop “Light Dark Matter,” University of California, Davis, Apr. 30 – May 1, 2010.
- Johns Hopkins workshop “Current Problems in Particle Theory,” May 23–25 2010.
- Aspen Summer Workshop “Colliders to the Dark Sector: Understanding Dark Matter at Particle Colliders and Beyond” June 20–July 18, 2010.
- Fifth CERN-Fermilab Hadron Collider Physics Summer School, August 16–27, 2010.
- Workshop on Topologies for Early LHC Searches, SLAC National Accelerator Laboratory, Menlo Park, California, Sep. 22–25. 2010.
- UC Davis HEFTI Workshop “Bubbles in the Sky,” University of California, Davis, Apr. 1–2, 2011.
- UC Davis HEFTI Workshop “The Tau Portal,” University of California, Davis, Apr. 7, 2011.
- UC Davis HEFTI Workshop “SUSY Recast,” University of California, Davis, Apr. 8–9, 2011.

- KITP Workshop “The First Year of the LHC,” The Kavli Institute for Theoretical Physics, University of California, Santa Barbara, June 13 – July 1, 2011.
- Berkeley Center for Theoretical Physics workshop on dark matter, April 29–May 1, 2011.
- UC Davis HEFTI Workshop “Hidden SUSY,” University of California, Davis, Nov. 8–9, 2011.
- ICTP Workshop “Strongly Coupled Physics Beyond the Standard Model,” January 25–27, 2012.
- Workshop “Back to the Bootstrap II” Perimeter Institute, June 11-15, 2012.

2.6 Terning

2.6.1 Recent Highlights

Most of Terning’s work is related to electroweak symmetry breaking in various ways. With the arrival of the LHC, the stabilization of electroweak symmetry breaking with respect to quantum corrections remains the most pressing theoretical issue, and the most exciting since we should soon have the data needed to guide us in the right direction. What follows are some highlights of Terning’s work over the past three years. Details may be obtained from the papers listed in section 2.6.2.

- **Natural SUSY**

  Csaki, Shirman, and Terning returned to looking a strongly coupled supersymmetric models where some of the standard model particles are composite. They found a new, relatively simple model where the top, the Higgs, and the W and Z are composite [9]. The Higgs can easily be as heavy as 125 GeV, unlike many other supersymmetric models, and the top yukawa coupling is naturally of order one. These models were examined further with Csaki and Randall by including SUSY breaking [6]. It turns out that the leading contribution to the soft masses of the composite particles are determined by Seiberg duality and holomorphy. The result is that the composite superpartners, like the stops and left-handed sbottom, are much lighter that the elementary superpartners, the other squarks, sleptons, and gluino. In fact the lightest stop can be nearly degenerate with the top. A spectrum with stops much lighter than other squarks fits in well with the early LHC results that put stringent constraints on degenerate squarks as well as gluinos. Having a light stop is crucial for maintaining naturalness in SUSY theories. So this model provides a straightforward way to maintain naturalness without the arbitrary adjustment of squark masses. As part of this project, software was developed and provided to the community (at `https://github.com/jterning/MCSSMTools`) to calculate the spectrum and branching fractions for the complete spectrum of the model. It is hoped that this will proved useful for developing LHC searches for the unique features of the model. A student, R. Houtz, is currently working on Monte Carlo simulations for this model using Madgraph and the MCSSMTools software that Terning developed.

- **Composite Higgs**

  While the work mentioned above provides a very detailed model for a composite SUSY Higgs sector, it is also worthwhile to approach the scenario of a composite Higgs from a model independent perspective. If the Higgs is composite it couplings will probably deviate from standard model values, in which case it may not provide the required unitarization of WW

scattering. If the calculated scale of unitarity violation is too low, then there must be additional states that contribute to the unitarization. Terning and collaborators [3] studied the simplest possibility where there is a single spin-1 particle that provides the contributions needed for unitarization. This is a simplified version of many extra dimensional models where there are a tower of KK mode "excitations" of the W and Z. Usually in such extra dimensional models the lowest KK mode dominates the unitarization. The requirement of unitarization significantly reduces the number of free parameters in the low-energy effective theory, which makes a detailed analysis tractable. Interestingly while composite Higgs particles usually have suppressed couplings to photons (as in gaugephobic Higgs models, for example) the extra spin-1 state contributes through a loop (just like the W) and can give rise to an enhanced Higgs to two photon width, as is hinted at in the preliminary LHC data.

- **SUSY Breaking**

  If superpartners are found at the LHC, we will still need to know how supersymmetry has been broken in the vacuum. The advent of Seiberg duality lead to a burst of development of new models of SUSY breaking. Recently there has been additional exploration, following Intriligator, Seiberg, and Shih, of models where the SUSY breaking vacuum state is only a (metastable) local minimum. Recently Terning and collaborators [7] were able to open up a new class of SUSY breaking models. Starting with an $\mathcal{N} = 1$ SUSY model and making use of Seiberg-Witten techniques to uncover regions with light monopoles or dyons, it was shown that in the low-energy effective theory the condensation of monopoles or dyons drives SUSY breaking. These models also feature a metastable minimum with R-symmetry breaking which can make it much easier to get a large gluino mass.

- **Unhiggs Phenomenology**

  From the perspective of the gaugephobic Higgs model one can see that something interesting happens when the scaling dimension of the composite Higgs field goes below 2. Then, even though it is very different from the Standard Model Higgs, one can study the phenomenology with a 4D effective field theory. Another way of saying this is that the Higgs could be what Howard Georgi calls an "unparticle". With a student, D. Stancato, Terning examined a model where the role of the Higgs is played by a weakly coupled composite operator of some new conformal sector. This "Unhiggs" has a scaling dimension larger than one, and its mass operator can have a scaling dimension close to four. This implies that the UnHiggs has a softer mass divergence than the ordinary Higgs, which can help solve the "little hierarchy problem" (why the weak scale is small compared to the LEP bounds, around 10 TeV, on new physics contributing through higher dimension operators). Since the longitudinal components of the W and Z come from the Unhiggs there would be an effect in top quark decays. Data from the Tevatron are not particularly constraining in this respect but the effect could be seen at the LHC [13]. Further work was done with Englert and Spannowsky [5] on the nontrivial unitarity constraints that arise from the $t\bar{t} \to WW$ process if the scaling dimension is between 1.5 and 2. Analysis was done on the experimental constraints that will arise from the four lepton final state ($pp \to H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$). Finally, full Monte Carlo simulations were performed [4] and compared with early LHC data. For Unhiggs masses above 200 GeV, the four lepton final state is sufficiently simple that a naive PGS detector simulation is sufficient to extract meaningful bounds on the scaling dimension [4]. We hope that experimentalists will be able to take our results and extend the bounds below 200 GeV where a full detector analysis is required. This Unhiggs analysis provides another way to quantify how Standard Mode-like the resonance discovered at the LHC actually is.

- **Continuum Superpartners**

  With Hsin-Chia Cheng, our former postdoc A. Medina, and a former student, H. Cai, Terning studied models with supersymmetric unparticles. In these models there can be a gap between the particle and the corresponding unparticle continuum. In the supersymmetric limit, there is a superpartner that is degenerate with the particle and a superpartner unparticle continuum that has the same threshold as the unparticle continuum. With supersymmetry breaking, the superpartner mass can move up, even though the continuum thresholds stay degenerate in the simplest case. The superpartner can even move up into (and be lost in) the continuum region. In this case the superpartner of a particle is just an unparticle continuum rather than an actual particle. It will be very challenging to uncover such a scenario at the LHC, but progress has been made in understanding the phenomenology of these models [8]. Starting in the continuum, a gluino could decay into a quark and a squark, but the squark can decay back to a quark and a gluino and so on. It was shown that the narrow width approximation can be used to analyze these decay chains, even though the continuum states do not have a mass shell [8]. With this result Monte Carlo simulations can be performed with a dense set of particles representing the continuum states.

- **Dilatons**

  With collaborators Terning studied whether the light, higgs-like, 125 GeV scalar resonance can be interpreted as a dilaton [1]. This has been thoroughly examined in the extra dimensional Randall-Sundrum model, but not from a more model independent perspective. While this could work in a Randall-Sundrum model, it is not generic and is very unlikely to arise in a strongly coupled 4D theory without a flat direction. Flat directions usually only appear in SUSY theories. However using the AdS/CFT correspondence it was found that a CFT with a almost marginal operator could produce a light dilaton if the anomalous dimension was about 1/100. If most or all of the other standard model particles are not part of the CFT then the couplings of the dilaton can be very similar to a higgs if conformal and electroweak symmetry are broken by the same VEV.

- **Monopole Condensation and Electroweak Symmetry Breaking**

  Csaki, Shirman, and Terning have also been thinking about a class of models where electroweak symmetry breaking is triggered by monopole condensation. If monopoles were added to the Standard Model, they would have to have magnetic hypercharges. Since Dirac showed that electric and magnetic couplings are inversely proportional, such monopoles would be strongly coupled, and this strong coupling could drive electroweak symmetry breaking as in Technicolor models. Since there is no elementary higgs in this model and no new gauge coupling there are actually fewer parameters than in the Standard Model. They found that there are new types of anomaly constraints [12] that have to be satisfied, but that a model with a single generation of monopoles is anomaly free with particular magnetic hypercharge assignments [11]. One might expect that the corrections to precision electroweak measurements in this case would be similar to an extra generation model. Such extra generation models are not currently ruled out. A major failing of technicolor models (among several, including not having a higgs-like excitation) is the difficulty in getting a large enough top quark mass without introducing flavor-changing-neutral-currents. This problem can be solved with monopoles through the Rubakov-Callan effect [11]. It is possible that this type of has a light dilaton excitation that could play the role of the higgs.

- **Other**

A small fraction of time was devoted to the Particle Data Group collaboration's efforts to maintain and keep the "Review of Particle Properties" [2, 10] up to date.

2.6.2 Publications and Talks since 2010

The following is a list of Terning's papers and talks.

References

[1] B. Bellazzini, C. Csaki, J. Hubisz, J. Serra and J. Terning, "A Higgslike Dilaton," Eur. Phys. J. C **73** (2013) 2333 [arXiv:1209.3299 [hep-ph]].

[2] J. Beringer *et al.* [Particle Data Group Collaboration], "Review of Particle Physics (RPP)," Phys. Rev. D **86** (2012) 010001.

[3] B. Bellazzini, C. Csaki, J. Hubisz, J. Serra and J. Terning, "Composite Higgs Sketch," arXiv:1205.4032 [hep-ph].

[4] C. Englert, D. Goncalves-Netto, M. Spannowsky and J. Terning, "Constraining the Unhiggs with LHC data," arXiv:1205.0836 [hep-ph].

[5] C. Englert, M. Spannowsky, D. Stancato and J. Terning, "Unconstraining the Unhiggs," arXiv:1203.0312 [hep-ph].

[6] C. Csaki, L. Randall and J. Terning, "Light Stops from Seiberg Duality," arXiv:1201.1293 [hep-ph].

[7] C. Csaki, D. Curtin, V. Rentala, Y. Shirman, J. Terning, "Supersymmetry Breaking Triggered by Monopoles," [arXiv:1108.4415 [hep-ph]].

[8] H. Cai, H. -C. Cheng, A. D. Medina, J. Terning, "SUSY Hidden in the Continuum," [arXiv:1108.3574 [hep-ph]].

[9] C. Csaki, Y. Shirman, J. Terning, "A Seiberg Dual for the MSSM: Partially Composite W and Z," [arXiv:1106.3074 [hep-ph]].

[10] K. Nakamura *et al.* [Particle Data Group Collaboration], "Review of particle physics," J. Phys. G **G37**, 075021 (2010).

[11] C. Csaki, Y. Shirman, J. Terning, "Electroweak Symmetry Breaking From Monopole Condensation," Phys. Rev. Lett. **106**, 041802 (2011). [arXiv:1003.1718 [hep-ph]].

[12] C. Csaki, Y. Shirman and J. Terning, "Anomaly Constraints on Monopoles and Dyons," Phys. Rev. D **81** (2010) 125028 [arXiv:1003.0448 [hep-th]].

[13] D. Stancato and J. Terning, "Constraints on the Unhiggs Model from Top Quark Decay," Phys. Rev. D **81** (2010) 115012 [arXiv:1002.1694 [hep-ph]].

Talks

1. "Dilatons and Fine Tuning," SLAC, May 1, 2013.

2. “Dilatons and Fine Tuning,” Cornell, Mar. 27, 2013.
3. “A Light Composite Stop,” Frontiers Beyond the Standard Model III, Oct. 11-13, 2012.
4. “A Light Composite Stop,” Fermilab, Oct 10, 2012.
5. “A Light Composite Stop,” U. of Oregon, Sep. 25, 2012
6. “A Light Composite Stop,” SLAC, Stanford, Dec. 2, 2011
7. “Monopoles and Electroweak Symmetry Breaking,” Dirac Lecture, Florida State University, Tallahassee, Nov. 30, 2011
8. “Seiberg-Witten Monopoles,” Dirac Lecture, Florida State University, Tallahassee, Nov. 29, 2011
9. “Electric-Magnetic Duality to Seiberg Duality,” Dirac Lecture, Florida State University, Tallahassee, Nov. 28, 2011
10. “A Light Composite Stop,” Cornell, Nov. 18, 2011
11. “Monopoles and Electroweak Symmetry Breaking,” Institute for Advanced Study, Princeton, Oct. 27, 2011
12. “Monopoles and Electroweak Symmetry Breaking,” U. Pittsburgh, Oct. 25, 2011
13. “Monopoles and Electroweak Symmetry Breaking,” 23rd Rencontres de Blois Particle Physics and Cosmology, May 29-June 3, 2011.
14. “Unitarity and Nonlinear Boundary Conditions,” Cornell, Mar. 16, 2011
15. “Monopoles and Electroweak Symmetry Breaking,” 2011 Aspen Winter Conference ”New Data from the Energy Frontier,” Feb. 13-18, 2011.
16. “Monopoles, Anomalies, and Electroweak Symmetry Breaking,” Cornell, Nov. 23, 2010
17. “Monopoles, Anomalies, and Electroweak Symmetry Breaking,” UC Berkeley, Sep. 20, 2010.
18. “Monopoles, Anomalies, and Electroweak Symmetry Breaking,” U. Southampton, England, Apr. 26, 2010.
19. “Monopoles, Anomalies, and Electroweak Symmetry Breaking,” EPFL, Lausanne Switzerland, Apr. 26, 2010.
20. “Monopoles, Anomalies, and Electroweak Symmetry Breaking,” U. di Roma La Sapienza, Italy, Apr. 23, 2010.
21. “Monopoles, Anomalies, and Electroweak Symmetry Breaking,” U. Warsaw, Poland, Apr. 19, 2010.
22. “Monopoles, Anomalies, and Electroweak Symmetry Breaking,” MC4BSM, Copenhagen Denmark, Apr.14-16, 2010.
23. “Higgsless Models”, Rencontres de Moriond, La Thuille Italy, Mar. 7-13, 2010.
24. “Monopoles, Anomalies, and Electroweak Symmetry Breaking,” CERN, Feb 5, 2010.
25. “Monopoles, Anomalies, and Electroweak Symmetry Breaking,” Rencontres de Physique des Particules, Lyon France, Jan 25-27, 2010.

2.7 Workshops

During the January, 2010 to April, 2013 period, the combined PIs of the UC Davis DOE grant engaged in a program of small focused theory/experiment workshops in particle physics and cosmology to facilitate the interaction between theorists and experimentalists needed to realize the full potential of the investment by DOE and other science funding agencies in the ambitious and exciting research programs they sponsor. These were supported by the UC Davis HEFTI initiative, which expired June 2013. There were a total of 12 such workshops on a range of topics that bring together theorists and experimentalists. Full workshop information including participants, talks, and audio of discussions can be found on the web at

`http : //particle.physics.ucdavis.edu/workshops/`

The format of these workshops was to have approximately equal numbers of theorists and experimentalists, brought together for 2 days of focussed discussion. The format is very open and informal, with very few talks. The primary aim is to stimulate discussion about next steps, with just enough presentation of current results to set the stage. We have found this format to be much more productive than a full schedule of talks. We believe that UC Davis was one of the very first to hold such workshops repeatedly and systematically, and the currently increasing popularity of these workshops is largely due to our pioneering efforts in this direction.

Our past workshops have been extremely lively and have led directly to many new collaborations or research projects by the participants. Many of our participants have stated that these were among the very best workshops they have attended, that they formed collaborations, and/or that they had a significant impact on their subsequent research. Experimentalists have been especially enthusiastic about these workshops.

3 Task B2: Theoretical Cosmology

PI's: **Andreas Albrecht**, **Nemanja Kaloper** and **Lloyd Knox**

3.1 Task B2 Overview

Cosmology provides a context where deep aspects of fundamental physics can be closely tied to precision observations. From dark energy to dark matter to cosmic inflation, cosmology offers some of the most compelling signs of physics beyond the standard model of particles and offers powerful probes of new physics. The Task B2 PI's have very strong track records in the broad range of research areas that are linked together by cosmology. During the review period our research program has continued to thrive. We have made influential advances on a wide range of topics, from fundamental questions about gravity and time to topics in superstring cosmology, cosmic inflation and other early universe phenomenology, as well as the physics of black holes. Our work helps shape the planning of new experiments and develops the fundamental theory that these new experiments will probe. One measure of the impact of this work is the large number of citations and prominent invited talks given by the PI's during the review period (detailed below). Finally, in this review cycle we are adding Lloyd Knox as a Co-PI, applying for support for his activities in theoretical cosmology, separately from his work on other theoretical aspects of cosmological data analysis which are funded by other grants (and proposed also on task T of this grant). For Albrecht and Kaloper, we specifically present past accomplishments supported by DOE task B2 in the review period starting July 2009. For Knox, we present past accomplishments only as we feel appropriate to make the case for the proposed Knox research program.

3.2 Task B2 Mentoring

Albrecht and Kaloper have also continued their excellent record of mentoring. We are pleased to have on board Norihiro Tanahashi (from Kyoto University) who began a postdoctoral appointment with us starting in Fall 2010. Past postdocs such as M. Kaplinghat and L. Sorbo are thriving in faculty positions at prominent universities, and both are tenured. Martin Sloth has won a prestigious Lunbeck fellowship in Denmark, and has taken a tenured associate professor position the University of Southern Denmark. Minjoon Park has moved on to his new postdoctoral appointment, at the University of Massachusetts in Amherst. Alberto Iglesias, after having moved on to a postdoc at LMU in Munich with Gia Dvali, has left the field to go into finance.

Albrecht and Kaloper have supervised several graduate students during the review period (A. Abrahamse, N. Bolis, B. Bozek, A. Hernley, D. Phillips, M. Sandora, A. Scacco and A. Ulvestad). As detailed below, the students and postdocs have had a significant role in the productivity of task B2.

An increasing number of incoming UC Davis students seek out the PI's as supervisors, but due to ongoing growth of the UC Davis physics department it is no longer possible to continue mentoring this many graduate students based almost entirely on TA support as we have done in the past. Meanwhile, much of the justification for science funding from Washington is based on the importance of providing young people with strong scientific training. Both these factors point to the importance of moving away from the DOE HEP tradition of minimal funding for theorists. We are grateful for recent improvements in B2 funding for students and will continue to advocate in support of this trend.

Knox has an outstanding mentoring record as well. To date he has graduated six students who all moved on to postdoc positions, and one of them, Yong-Seon Song, has recently started a faculty position in Korea. Knox has also mentored four postdocs, Jean-Baptiste Melin, Mario Santos, Hu Zhan, and Manoj Kaplinghat, and all of them currently hold permanent positions in physics. Clearly, this contributes to the great promise for continued success of the enlarged B2 group in mentoring young people.

Significantly, a number of students and postdocs (notably Abrahamse, Kaplinghat, Song and Zhan) have been jointly supported and mentored by Knox and at least one of Albrecht and Kaloper. Thus in practice all three PI's have already been functioning successfully as a group with overlapping research interests and activities. The proposal to have Knox join B2 is intended to build on these successes as Knox's commitments to specific experiments reduce sufficiently for him to devote more time to basic research in theoretical cosmology.

3.3 Task B2 Project Highlights: Research completed July 2009 - July 2012

(B2 authors listed in italics, papers from the B2 papers list are cited by author and number on the list)

de Sitter Equilibrium cosmology (Albrecht)
A period of 60 e-foldings of inflation in the early universe appears to have an extremely successful phenomenology. In order to understand the theory fully, and even to know what the predictions really are, the theory must have a completion. The completion must address a number of subjects including what field is driving inflation, how inflation started and the domain of validity of the effective field theory of the inflaton. (Some of the current problems associated with finding such a completion are discussed in the proposed research section.) The de Sitter equilibrium cosmology (dSE) is one proposed completion of inflation theory, one that is finite and thus avoids the multiple difficulties associated with the infinities of the popular "eternal inflation" completion. Albrecht paper 4 developed dSE cosmology further and addressed some of the standard questions about it.

Cosmic Curvature from de Sitter Equilibrium cosmology (Albrecht)

Albrecht showed that the dSE picture makes a reasonably robust prediction for a level of cosmic curvature consistent with current bounds but still observable with future experiments. A short paper on the curvature work (Albrecht paper 2) appeared ina PRL, and a long paper that develops this work further is part of the proposed research.

Properties of Thick Wall Bubbles (Albrecht & Ulvestad)

The Farhi-Guth-Guven (FGG) process [1] is a tunneling process for producing a baby universe. The dSE picture depends critically on this process, especially to evade the Boltzmann Brain problem. Some have argued that the certain peculiar behaviors of the FGG process in the small bubble limit suggest that is an unphysical process and should not be counted in cosmological scenarios. With grad student Ulvestad, Albrecht showed that the problematic limiting behavior was due to the thin wall approximation used in earlier papers. Albrecht paper 1 calculates the more realistic thick wall case (where full solutions to the scalar field equations are used to describe the bubbles) countering the unphysicality arguments.

Understanding ergodicity in the cosmos (Albrecht)

The thermodynamic arrow of time can be traced to the low entropy properties of the Universe with respect to gravitational collapse. In this way the second law of thermodynamics is linked to the homogeneity of the early universe (which has a gravitational entropy down by over 30 orders of magnitude from the maximal value set by Λ). It is widely believed that the corresponding 14 Gyr history of increasing entropy precludes an equilibrium picture of the universe which would surely favor smaller downward fluctuations in entropy. Albrecht has developed toy models that demonstrated how the cosmological theories can evade this problem (namely by making the universe part of a larger system from which point of few the standard big bang *is* a smaller fluctuation). This work has been presented extensively at conferences and a paper is in preparation.

Understanding infinities in the cosmos (Albrecht & Hernley)

Albrecht has also developed toy models to illustrate the dependence of eternal inflation-like inflation completions on assumptions about infinities in time and phase space. I use these toy models to argue that this dependence on infinities appears to be quite problematic. This work has been presented extensively at conferences and a paper (further developing these toy models with Hernley) is in preparation.

Lorentz Symmetry from a Random Hamiltonian (Albrecht & Iglesias)

In earlier work we have argued that quantum cosmology considerations may make the laws of physics we observed to be essentially drawn at random from a huge range of possibilities, and argued that local field theories were favored [3] outcomes of these random draws. In Albrecht paper 3 we showed that the random selection process favors field theories with Lorentz symmetric dispersion relations.

Effects of Inhomogeneity on the Causal Entropic prediction of Lambda (Phillips & Albrecht)

The Causal Entropic Principle (CEP) is another attempt to control the measure problems of eternal inflation [3]. Albrecht paper 5 demonstrates the importance of including inhomogeneities in the application of the CEP (all previous work used a homogeneous ansatz). Our results impact the CEP constraints in interesting ways that change how the CEP might eventually fit into a larger picture.

Curvature Causal Entropic prediction of Lambda (Bozek, Phillips & Albrecht)

This collaboration was the first to explore the implications of including curvature when calculating predictions from the Causal Entropic Principle (CEP). We found the CEP predicts a somewhat larger value of the cosmic curvature than is observed, but (depending on priors) not necessarily sufficient to rule out the CEP. (Albrecht paper 8).

Forecasting for future dark energy experiments (Albrecht)

Continuing work initiated by calculations for the Dark Energy Task Force [4], Albrecht contributed to two whitepapers submitted to the Astronomy & Astrophysics decadal survey (Albrecht papers 6 & 7), as well as the 2012 "DOE Community Dark Energy Task Force" report.

Topological Ghosts (Kaloper and Sandora)

In recent years there has been much discussion about making universes bounce through singularities. If one violates null energy conditions one could construct cosmologies which may bounce by, avoiding singularities. Typically this involves field theoretic ghosts: local degrees of freedom which have unbounded Hamiltonian and so can yield rapid local instabilities. One may avoid typical field theory ghosts by invoking models where null energy violating sectors do not contain any propagating degrees of freedom. This occurs when one introduces volume-filling form fields with "wrong sign" kinetic terms, such as in so-called Type-II^* string theories. Locally, these form fields are just additive renormalizations of the cosmological constant. However, once the fields are coupled to membranes charged under them, there arise catastrophic non-perturbative instabilities induced by membrane nucleations, analogous to Schwinger processes with imaginary charges. If the background cosmological constant is positive, a (negative) flux contribution to it rapidly discharges away, leaving a bare cosmological constant unscreened. If the background cosmological constant is zero or negative, the flux rapidly grows large generating an even more negative net cosmological constant. Such processes quickly drive a negative cosmological constant to the cutoff of the theory. So using negative kinetic terms of form fields in cosmological phenomenology would imply that any universe would in fact rapidly collapse after inflation ends. (Kaloper publication 1)

Cutoffs, Stretched Horizons and Black Hole Radiators (Kaloper)

Kaloper argued that if the UV cutoff of the IR theory is of the order, or below, the scale of the stretched horizon in a black hole background, which in turn is significantly lower than the Planck scale, the black hole radiance is controlled by the UV completion of the field theory. In particular, if the UV completion of the theory involves degrees of freedom which cannot be efficiently emitted by the black hole, the naive radiance rate estimated by the counting of the IR degrees of freedom may be dramatically reduced. If we apply this argument to the RS2 brane world, it implies that the emission rates of the low energy CFT modes will be dramatically suppressed: its UV completion is given by the bulk gravity on $AdS_5 \times S^5$, and the only bulk modes that could be emitted by a black hole are the s-waves of bulk modes with small 4D masses. But their emission is suppressed by bulk warping. This lowers the radiation rate much below the IR estimate, and follows directly from low CFT cutoff $\mu \sim L^{-1} \ll M_{Pl}$, a large number of modes $N \gg 1$ and the fact that 4D gravity in RS2 is induced, $M_{Pl}^2 \simeq N\mu^2$. (Kaloper publication 2)

Galileon Hairs of Dyson Spheres, Vainshtein's Coiffure and Hirsute Bubbles (Kaloper, Tanahashi & external collaborator)

In recent work on modification of gravity a key role is played by the so called Vainshtein mechanism. This mechanism proposes that additional long range forces in modified theories, mediated by additional long range modes, can be suppressed by environmental mechanisms, which essentially involve background-dependent classical 'renormalization' of kinetic terms. These in turn change the Gauss law for the affected degrees of freedom, and so alter - i.e. weaken - their long range fields. Kaloper, Padilla and Tanahashi have studied this phenomenon for spherically symmetric thin shell sources, a.k.a. Dyson spheres, in a *fully nonlinear covariant* theory of gravity with the simplest galileon field, in effect providing the *first* analytical proof of the mechanism while also pointing out the limits on its regime of validity. They found that the field equations can all be integrate exactly once in this case, and reduced them to a system first order nonlinear equations. The resulting equations are highly nonlinear and admit different branches. For the simplest galileon, static solutions come on *six* distinct branches. On one, a Dyson sphere surrounds itself with a galileon hair, which far away looks like a hair of any Brans-Dicke field. The hair changes below the Vainshtein scale, where the extra galileon terms dominate the minimal gradients of the field. Their hair looks more like a fuzz, because the galileon terms are suppressed by the derivative of the volume determinant. It shuts off the 'hair bunching' over the 'angular' 2-sphere. Hence the fuzz remains dilute even close to the source. This is really why the Vainshtein's suppression of the modifications of gravity works close to the source. On the other five branches, the static solutions are all *singular* far from the source, and shuttered off from asymptotic infinity. One of them, however, is really the self-accelerating branch, and the singularity is removed by turning on time dependence. They gave examples of regulated solutions, where the Dyson sphere explodes outward, and its self-accelerating side is nonsingular. These solutions may open channels for nonperturbative transitions between branches, which need to be addressed further to determine phenomenological viability of multi-branch gravities. (Kaloper publication 3)

An Ignoble Approach to Large Field Inflation (Kaloper & external collaborators)

Kaloper, Lawrence and Sorbo performed a detailed exploration of string theoretic model building approaches to examine when inflation with a quadratic potential, and more generally any large field inflation, may occur in string landscapes where an axion potential is generated by the mixing with 4-form fluxes. In such models, an axion is massive, but the mass is small, being protected by the (weakly broken) axion shift symmetry. The 4-form backgrounds break this symmetry and comprise a mini-landscape, where their fluxes can change by emission of membranes. Inflation can begin when the 4-form dominates the energy density. Such models are experimentally the most interesting because they are the best mechanism for producing primordial gravitational waves during inflation. (Kaloper publication 4)

McVittie's Legacy: Black Holes in an Expanding Universe (Kaloper, with Kleban and Martin)

The main result of this work is the proof that a class of solutions to Einstein's equations—originally discovered by G. C. McVittie in 1933—includes regular black holes embedded in Friedman-Robertson-Walker cosmologies. If the cosmology is dominated at late times by a positive cosmological constant, the metric is regular everywhere on and outside the black hole horizon and away from the big bang singularity, and the solutions asymptote in the future and near the horizon to the Schwarzschild-de Sitter geometry. For solutions without a positive cosmological constant the would-be horizon is a weak null singularity. (Kaloper publication 5)

String Axiverse (Kaloper & external collaborators)

With Arvanitaki, Dimopoulos, Dubovsky and March-Russell, Kaloper investigated how upcoming astrophysical experiments will explore the existence of such axions over a vast mass range from 10^{-33} eV to 10^{-10} eV. In addition to their known cosmological signatures, the axions can affect the dynamics and gravitational wave emission of rapidly rotating astrophysical black holes through the Penrose superradiance process, if their masses range between 10^{-22} eV and 10^{-10} eV. When the axion Compton wavelength is of order of the black hole size, the axions develop "superradiant" atomic bound states around the black hole "nucleus". Their occupation number grows exponentially by extracting rotational energy from the ergosphere, culminating in a rotating Bose-Einstein axion condensate emitting gravitational waves. This creates 'gaps' in the spectrum of rapidly rotating black holes that diagnose the presence of axions. Subsequent exploration by Arvanitaki and Dubovsky has confirmed this in more detail. (Kaloper publication 6)

Gravitational wave signal from massive gravity (Tanahashi & external collaborators)

Tanahashi and collaborators discussed the detectability of gravitational waves with a time dependent mass contribution, by means of the stochastic gravitational wave observations. The primary manifestation of the modification in the gravitational wave spectrum is a sharp peak. The position and height of the peak carry information on the present value of the mass term, as well as the duration of the inflationary stage. (Tanahashi publication 1)

Instability in near-horizon geometries of even-dimensional Myers-Perry black holes (Tanahashi & an external collaborator)

Tanahashi and Murata studied the gravitational, electromagnetic and scalar field perturbations on the near-horizon geometries of the even-dimensional extremal Myers-Perry black holes. The result suggests that the even-dimensional (near-)extremal Myers-Perry black holes are unstable against gravitational perturbations. They also discussed implications of their results to the Kerr-CFT correspondence.(Tanahashi publication 2)

Hawking temperature for near-equilibrium black holes (Tanahashi & an external collaborator)

Tanahashi and collaborator discussed Hawking temperature of near-equilibrium black holes using a semiclassical analysis. As an example of applications of these results, they studied the Hawking temperature of black holes with null shell accretion in asymptotically flat space and the AdS-Vaidya spacetime. They discussed implications of our results in the context of the AdS/CFT correspondence. (Tanahashi publication 3)

Black holes in braneworld models (Tanahashi & an external collaborator)

Takahashi and Tanaka wrote a review summarizing the current understandings of black hole solutions in various braneworld models, including the Arkani-Hamed-Dimopoulos-Dvali model, the Randall-Sundrum (RS) models, the Karch-Randall (KR) model and the Dvali-Gabadadze-Porrati model. (Tanahashi publication 4)

Probing the size of extra dimension with gravitational wave astronomy (Tanahashi & external collaborators)

In Randall-Sundrum II (RS-II) braneworld model, it has been conjectured according to the AdS/CFT correspondence that brane-localized black hole (BH) larger than the bulk AdS curvature scale l cannot be static, and it is dual to a four dimensional BH emitting the Hawking radiation through some quantum fields. In this scenario, the number of the quantum field species is so large that this radiation changes the orbital evolution of a BH binary. Tanahashi and collaborators derived the correction to the gravitational waveform phase due to this effect and estimated the upper bounds on l by performing Fisher analyses. They found that DECIGO/BBO can put a stronger constraint than the current table-top result by detecting gravitational waves from small mass BH/BH and BH/neutron star (NS) binaries. Furthermore, DECIGO/BBO is expected to detect 10^5 BH/NS binaries per year. Taking this advantage, they found that DECIGO/BBO can actually measure l down to $l = 0.33\mu$m for 5 year observation if we know that binaries are circular a priori. This is about 40 times smaller than the upper bound obtained from the table-top experiment. On the other hand, when the eccentricities are taken into binary parameters, the detection limit weakens to $l = 1.5\mu$m due to strong degeneracies between l and eccentricities. They also derived the upper bound on l from the expected detection number of extreme mass ratio inspirals (EMRIs) with LISA and BH/NS binaries with DECIGO/BBO, extending the discussion made recently by McWilliams. These less robust constraints are weaker than the ones from phase differences. (Tanahashi publication 5)

Angular momentum at null infinity in five dimensions (Tanahashi & external collaborators)

In this paper, using the Bondi coordinates, Tanahashi and collaborators discuss the angular momentum at null infinity in five dimensions and address the Poincare covariance of the Bondi mass and angular momentum. (Tanahashi publication 6)

Knox was not supported by DOE in the previous period.

3.4 Task B2: Papers July 2009 - July 2012

List of Publications and Preprints (Albrecht)

1. A. Ulvestad and A. Albrecht, “Creating universes with thick walls,” Phys. Rev. D **85**, 103527 (2012)

2. A. Albrecht, “Cosmic curvature from de Sitter equilibrium cosmology,” Phys. Rev. Lett. **107**, 151102 (2011)

3. A. Albrecht and A. Iglesias, “Lorentz symmetry from a random Hamiltonian,” arXiv:1003.2566 [hep-th].

4. A. Albrecht, “de Sitter equilibrium as a fundamental framework for cosmology,” J. Phys. Conf. Ser. **174**, 012006 (2009)

5. D. Phillips and A. Albrecht, “Effects of Inhomogeneity on the Causal Entropic prediction of Lambda,” Phys. Rev. D **84**, 123530 (2011)

6. H. Zhan, A. Albrecht, A. Cooray, S. Habib, A. Heavens, K. Heitmann, B. Jain and M. J. Jee *et al.*, “Exploring Dark Energy with Next-Generation Photometric Redshift Surveys,” arXiv:0902.2599 [astro-ph.CO].

7. R. Scranton, A. Albrecht, R. Caldwell, A. Cooray, O. Dore, S. Habib, A. Heavens and K. Heitmann *et al.*, “The Case for Deep, Wide-Field Cosmology,” arXiv:0902.2590 [astro-ph.CO].

8. B. Bozek, A. Albrecht and D. Phillips, “Curvature Constraints from the Causal Entropic Principle,” Phys. Rev. D **80**, 023527 (2009)

List of Publications and Preprints (Kaloper)

1. N. Kaloper and M. Sandora, *Topological Ghosts*, preprint (Supported by DOE).

2. N. Kaloper, *Cutoffs, Stretched Horizons and Black Hole Radiators,* arXiv:1203.3455 [hep-th] (Supported by DOE).

3. N. Kaloper, A. Padilla and N. Tanahashi, “Galileon Hairs of Dyson Spheres, Vainshtein’s Coiffure and Hirsute Bubbles,” JHEP **1110**, 148 (2011) [arXiv:1106.4827 [hep-th]] (Supported by DOE).

4. N. Kaloper, A. Lawrence and L. Sorbo, “An Ignoble Approach to Large Field Inflation,” JCAP **1103**, 023 (2011) [arXiv:1101.0026 [hep-th]] (Supported by DOE).

5. N. Kaloper, M. Kleban and D. Martin, “McVittie’s Legacy: Black Holes in an Expanding Universe,” Phys. Rev. D **81**, 104044 (2010) [arXiv:1003.4777 [hep-th]] (Supported by DOE).

6. A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper and J. March-Russell, “String Axiverse,” Phys. Rev. D **81**, 123530 (2010) [arXiv:0905.4720 [hep-th]] (Supported by DOE).

Other student and postdoc publications not already listed

1. A. E. Gumrukcuoglu, S. Kuroyanagi, C. Lin, S. Mukohyama and N. Tanahashi, “Gravitational wave signal from massive gravity,” arXiv:1208.5975 [hep-th] (Tanahashi supported by DOE).

2. N. Tanahashi and K. Murata, “Instability in near-horizon geometries of even-dimensional Myers-Perry black holes,” arXiv:1208.0981 [hep-th] (Tanahashi supported by DOE).

3. S. Kinoshita and N. Tanahashi, *Hawking temperature for near-equilibrium black holes,* Phys. Rev. D **85**, 024050 (2012) [arXiv:1111.2684 [hep-th]] (Tanahashi supported by DOE).

4. N. Tanahashi and T. Tanaka, “Black holes in braneworld models,” Prog. Theor. Phys. Suppl. **189**, 227 (2011) [arXiv:1105.2997 [hep-th]] (Tanahashi supported by DOE).

5. K. Yagi, N. Tanahashi and T. Tanaka, "Probing the size of extra dimension with gravitational wave astronomy," Phys. Rev. D **83**, 084036 (2011) [arXiv:1101.4997 [gr-qc]] (Tanahashi supported by DOE).

6. K. Tanabe, N. Tanahashi and T. Shiromizu, "Angular momentum at null infinity in five dimensions," J. Math. Phys. **52**, 032501 (2011) [arXiv:1010.1664 [gr-qc]] (Tanahashi supported by DOE).

7. A. Abrahamse, L. Knox, S. Schmidt, P. Thorman, J. A. Tyson and H. Zhan, Astrophys. J. **734**, 36 (2011) [arXiv:1011.2239 [astro-ph.CO]].

3.5 Task B2: Talks and other activities July 2009 - July 2012

3.5.1 Andreas Albrecht

Invited Talks at Major Meetings (Albrecht)

1. *Dark Energy: Current Status*, "PASCOS 2009," (Hamburg, July 2009)

2. *Challenges for a quantum theory of the Universe* "FQXI 2nd International Conference" (Ponta Delgada, Spain, July 2009)

3. *Challenges for a quantum theory of the Universe* "Conference on Holographic Cosmology" (Waterloo, July 2009)

4. *Cosmic Acceleration: Current theoretical issues and progress toward future observations* "Galileo-Xu Guangqui Meeting" (Shanghai, October 2009)

5. *Panelist*, "Experimental and Theoretical Challenges to Probing Dark Energy" (Palo Alto December 2011)

6. *New Results from de Sitter Equilibrium Cosmology* "Return of de Sitter" (Stockholm, Feb-March 2011)

7. *Panelist: Dark Energy* "Experiments on the Cosmic Frontier: Astrophysical Studies of Matter, Energy, Space and Time" (Fermilab, March 2011)

8. Infinity, Finiteness and Inflationary Cosmology "Challenges for Early Universe Cosmology" (Waterloo, July 2011)

9. *Dynamics, typicality and the arrow of time*, "Setting Time Aright," (Bergen, Copenhagen and points in-between, Aug 27-Sep 2 2011)

10. *Time, Infinity and Inflation*, "Inflationary Theory and its Confrontation with Data in the Planck Era," (Aspen, Feb 2012)

11. *Cosmology vs. Equilibrium* "Physics with a Positive Cosmological Constant" (Penn State, May 2012)

Albrecht has given numerous **Colloquia**, **Seminars**, **talks** at smaller workshops, public lectures, etc. during the review period.

Additional Activities (Albrecht)

1. Member, DOE Dark Energy Science Panel, 2012
2. Co-organizer, COSMO 2012 (Sep 2012, Beijing)
3. Editorial Board Member of Physical Review D 2010-2012
4. Astro 2010 Decadal Survey member of Particle Astrophysics and Gravity Panel (PAG) 2009-2010.
5. Member, Kavli Institute for Cosmological Physics External Advisory Board (2007-present).
6. Member, Astronomy and Astrophysics Advisory Committee (2011-present)
7. Service on numerous grant reviews

3.5.2 Nemanja Kaloper

Invited Talks at Major Meetings (Kaloper)

1. *Vainshtein's Coiffure*, **plenary talk**, Pre-Planckian Inflation workshop, University of Minnesota, 10/11/2011.
2. *Vainshtein's Coiffure*, **plenary talk**, workshop on Modified Gravity, ICTP, Trieste, Italy, 09/11/2011.
3. *Out of Darkness - The Story of* Λ, **plenary talk**, "New trends in the physics of the quantum vacuum: from condensed matter, to gravitation and cosmology", Trento, Italy, 06/29/2011.
4. *Slowly Rolling Axions from Flux Monodromy*, **plenary talk**, "Return of de Sitter", Nordita, Stockholm, 03/09/2011.
5. *Large Field Inflation, Ignobly*, **invited talk**, "String Theory and Precision Cosmology", Cornell University, 07/29/2011.
6. *Large Field Inflation, Ignobly*, **invited talk**, "Iberian Strings", University of Valencia, Spain, 02/16/2011.
7. *Large Field Inflation, Ignobly*, **invited talk**, Time and Matter, Budva, Montenegro, 10/07/2010.
8. *Large Field Inflation, Ignobly*, **invited talk**, COSMO/CosPA, University of Tokyo, Tokyo, Japan, 09/29/2010.
9. *Levitating Dark Matter*, **plenary talk**, IEU Workshop on Cosmology and Fundamental Physics, Institute for the Early Universe Ewha Womans University, Seoul, Korea, 05/17/2010.
10. *Large Field Inflation, Ignobly*, **invited talk**, APCTP-IEU Focus Program "Cosmology and Fundamental Physics", APCTP, Postech, Pohang, Korea, 05/12/2010.

11. *Some Comments on (Possible?) Signatures of Eternal Inflation*, **invited talk**, EFT in Inflation Workshop, University of Michigan, Ann Arbor, 03/12/10.
12. *A Natural Framework for Chaotic Inflation*, **plenary talk**, Grassmannian Conference in Fundamental Cosmology, University of Szczecin, Poland, 09/17/09.
13. *A Natural Framework for Chaotic Inflation*, **plenary talk**, Primordial Gravitational Waves Workshop, DAMTP, University of Cambridge, United Kingdom, 08/25/09.

Kaloper has also given a number of colloquia and seminars at various institutions during the review period.

Additional Activities (Kaloper)

1. Member of the Editorial Board of JCAP.
2. Member of the Editorial Board of Int. Jour. Phys. D.
3. Member of the Editorial Board of the European Jour. Phys. C.
4. Member of the DOE Early Career Grant Review Panel, 2010.
5. Member of the DOE Lab Theory Groups Review, July, 2011.
6. Organizer, "Bubbles in the Sky" 2-day mini-workshop, UC Davis, April 2011.
7. Member of the NSF Theory Review Panel, March 2012.
8. Member of the Organizing Committee, Cosmology and Gravity Workshop, Yukawa Institute, Kyoto, Japan.
9. Referee for DOE, NSF and Israeli Science Foundation proposals, Phys. Rev. Lett., Phys. Rev. **D**, JHEP, Phys. Lett. **B**, Int. J. Mod. Phys., Class. Quant. Grav. etc.

3.5.3 Lloyd Knox

Knox was not supported by DOE during this period. However we highlight his professional activities here.

Recent Invited Talks at Relevant Major Meetings (Knox)

1. *Neutrinos and Cosmology*, in the session Hot Topics in Astrophysics at the APS meeting, Atlanta, April 2012.
2. *Cosmology in the Era of the Large Hadron Collider'*, **plenary talk**, Pheno 2011, Madison, May 2011.

Knox gave seminars/colloquiua on neutrino cosmology at six institutions since May 2011.

Additional Activities (Knox)

1. External Reviewer for Cosmology at Los Alamos National Laboratory, March 2008.

2. Editor of the Journal of Cosmology and Astroparticle Physics (2006-2008).
3. Member of the Dark Energy Task Force (2005-2006).
4. Referee for DOE proposals, Phys. Rev. Lett., Phys. Rev. **D**, Astrophys. J.

3.5.4 Task B2 Students and postdocs

Students and Postdocs supported by Task B2 also have an impressive list of invited talks and other activities. Due to space limitations we do not list them all here. We believe the publications and career paths for these group members (documented elsewhere in this proposal) provides excellent evidence of their successes and progress.

3.6 Task B2 Project Objectives: Planned Research

3.6.1 Albrecht: Cosmology and Fundamental theory

Overview
Cosmological physics provides some of the strongest motivation for physics beyond the standard model of particles. Cosmological observations make the case for dark energy and dark matter, and the phenomenological success of cosmic inflation drives the theorist to ask what "inflaton" or other physics could have driven inflation. All of these topic pose fascinating theoretical problems, problems with deep ties to fundamental physics. These problems lie at the heart of Albrecht's proposed research. Although the problems are challenging, the presence of strong cosmological motivations and the promise of rapidly growing cosmological data sets with which to test new ideas make this an extremely promising and exciting areas of research.

As mentioned in Sect. 3.3 in connection with previous work, the fundamental theory (or "completion") behind inflation can have a lot to say about the ultimate observable predictions. The popular idea of "eternal inflation" (probably the most straightforward extrapolation of known physics) suffers from a host of problems associated with infinities (infinitely many pocket universes produced an each moment over an infinite amount of time), that prevent predictions from being made at all without an ad hoc regulator. Proponents are hopeful that some physically motivated regulator can be found, but so far this approach has not been successful. de Sitter Equilibrium (dSE) cosmology may through its finiteness present a way out of these problems, but the assumptions made about the underlying physics are controversial and need to be more closely examined and motivated. A large portion of Albrecht's proposed research is related in one way or another to the completion of cosmic inflation theory. Overall, the proposal is to build an interesting ongoing research program based on Albrecht's expertise and interest in these subjects. Here are some examples:

Continuations of current projects
Some projects listed in Sect. 3.3 (past work) are continuing. More specifics can be found in that section.

- *Cosmic Curvature from de Sitter Equilibrium* Long paper developing results reported in Albrecht paper 2.
- *Ergodicity in Cosmology* Develop existing work into a publication.

- *Infinities in Cosmology* Develop existing work into a publication.

Holography and Inflation

Albrecht paper 1 proposes a specific “holographic” bound on inflation. That bound is very different from those suggested by authors [5, 2, 6] who do not include the effects of a Λ (giving today’s acceleration). One other paper does include the effects of Λ [7] and appears to give the same result, although the specific framework does not appear to be at all the same. Phillips and Albrecht will analyze the relationship between these holographic results.

Probabilities and the Born Rule Crisis

Page [8] has pointed out that Born rule is insufficient to assign probabilities in a quantum theory of the universe where equivalent observers are represented by more than one set of degrees of freedom. This situation is expected to be commonplace in the eternal inflation picture, where the multiplicity of ourselves may well be infinite, and Page’s “‘Born Rule Crisis” (BRC) suggests yet another hurdle toward achieving predictive power in that picture. Albrecht made some initial progress on this topic over the review period (presented at conferences), and proposes to further develop this work into one or more publications. The central point is that essentially all responses to the BRC (including those by Page) [8, 9] as well as other work [10, 11] discussing probabilities in the multiverse have (either explicitly or implicitly) used probabilities very differently from the physically grounded usage in everyday situations, and thus introduces errors that could undermine the entire idea of the multiverse.

Bubble Curvature Values for dSE Cosmology

Albrecht papers 2 & 6 point to the importance of curvature “thick wall” bubbles (Ω_k^B in paper 2) and offer methods for exploring possible values of the bubble curvature. Albrecht proposes to pursue this path to understand what values of Ω_k^B are realistic, information which is key to fully understanding the predictions in paper 2.

Matrix Models of de Sitter Space

The dSE picture of cosmology makes certain assumptions about the fundamental quantum properties of de Sitter space, including finiteness. Finite models of de Sitter space have been proposed in [12]. Albrecht proposes to investigate these models to explore whether or not the properties assumed in the dSE work are in fact realized in the matrix models.

Dark matter annihilation and the Causal Entropic Principle

The causal entropic principle (CEP) has been discussed in Sect. 3.3. In the CEP, all sources of entropy production figure in to the ultimate predictions. This project will examine the entropic contributions from dark matter annihilations using different dark matter models and explore how such considerations may change predictions from the CEP.

The impact of current and future dark energy experiments

As plans continue for large dark energy experiments, and so-called “Stage 3” experiments start to yield new data, Albrecht plans to continue work to optimize both future experiments and the impact of existing data. This work started on the Dark Energy Task Force [4] and continued with Albrecht’s ongoing research program (see for example [13]) and includes contributions in 2012 to the DOE Community Dark Energy Task Force Report.

3.6.2 Kaloper: Theoretical Cosmology and High Energy Theory

Kaloper will continue to pursue research at the interface of high energy theory, cosmology and string theory, exploring the synergies between these areas, which is crucial at the time when cosmology is becoming a unique testing ground for fundamental physics at the TeV frontier.

Inflationary model building in field theory and string theory

In recent work with Sorbo and in its continuation with Lawrence and Sorbo [14], Kaloper has explored how the mixing of axions with topological 4-forms naturally yields $m^2\phi^2$ chaotic inflation models. These models are very similar to monodromy inflation [15]. The crux of these models is that the mixing generates a mass term which is radiatively protected by a shift symmetry that is only broken weakly by the 4-form background value. Such mechanisms can naturally emerge from dimensional reductions of supergravity theories with form fields and Chern-Simons couplings, and so it is very interesting to seek a precise embedding of such dynamics in string theory.

Kaloper and Lawrence have recently realized that the model may also be experimentally very interesting because, unlike typical large field inflation models, it may gives rise to significant quantum inflaton effects near the beginning of the last 65 efolds of inflation. This regime is akin to inflationary self-reproduction, which is usually separated from the last 65 efolds by a long regime of slow roll that makes the early quantum effects completely invisible. The flux monodromy setup with axions is different, and what happens is that bubbles which alter the 4-form flux may be nucleated as late as 65 efolds before the end of inflation. This could yield observable signatures on the sky, by altering the quantum dynamics of the inflation. However one also has to be weary of the domain walls as those tend to produce too strong effects. Yet, if domain walls decay later on, their dangerous effects could be completely avoided. Thus one must find a careful route between the dangers of domain walls and the benefit of the signatures of new physics. Currently Kaloper and Lawrence, along with Tanahashi, are setting up a program to study this in detail.

Holography and Inflation

Holographic principle has emerged as one of the underlying cornerstones of gravity. Its implications for cosmology are still vigorously debated, and it remains to determine just what its direct physical, and possibly observational, consequences may be. Recently Conlon, in a very interesting argument, has resurrected the idea that the holographic entropy bounds, based on the cosmological apparent horizon area, may obstruct inflation in UV-complete theories [16]. The specific model considered was N-flation [17], where the dynamics of inflation is powered by many pseudoscalar axions, which could be naturally light while still finding consistent UV parent models. The gist of the point which Conlon raised is that in such models one still needs to have large axion vevs, with (sub)Planckian axion decay constants, so that the longevity of inflation requires many fields to be simultaneously turned on. But, the presence of many fields in the cosmological background with a horizon, as the argument goes, would violate the holographic entropy bounds unless the veve of the axions, of the order of the cutoff of the theory, were much lower than the Planck scale. So, the conclusion would be that the holographic entropy bounds force a lower axion vev, which in turn limits the number of efolds to a mere $\mathcal{O}(1)$. However, upon a closer look one sees that Conlon's argument is in fact a manifestation of the 'species problem' [18] in a cosmological setting. Indeed, already in black hole physics it is known that if one uses a low energy theory with many (decoupled) light fields outside of a black hole, one will overshoot the Bekenstein-Hawking area law with field theory estimates, unless one takes a very low cutoff for the low energy theory [18]. This cutoff doesn't mean that the theory, or the background, cease to exist beyond it. Rather it implies that new physics is needed to properly understand what happens close to the horizon. In a black hole background, this is accounted for by the renormalization of the Planck scale in a precisely the same manner as the leading order divergence in the entropy, such that the number of species exactly cancels out [19]. With Sloth (University of Southern Denmark), Kaloper intends to prove that this also occurs in inflationary backgrounds, and develop a more precise description of inflation with many species, which can be phenomenologically successful and still demonstrably consistent with the holographic principle.

Long range forces in dark sector and their cosmological footprints

In recent work with Padilla, Kaloper explored the cosmological signatures of long range forces in the dark sector. The model which they considered assumes that a sizable fraction of the total energy density of the universe may be in heavy particles with a net dark $U(1)'$ charge equal to its mass, such that the forces which this $U(1)'$ mediates are comparable to gravity. When the charges have the same sign the cancellation between their gravitational and gauge forces may affect cosmological mass measurements significantly, and even mimic an extra 'antigravity', simulating dark energy equation of state smaller than the real one. In some cases, including that of a cosmological constant, these effects can mimic $w < -1$. These forces may also give a *local* variation of galaxy-galaxy forces, yielding a larger 'Hubble Flow' in those regions of space that could be taken for a dynamical dark energy, or superhorizon effects. This illustrates how the dark forces with long range can significantly affect our picture of the universe and contaminate the determination of cosmological parameters.

The general framework within which such questions may be asked is, how well does the "equivalence principle" apply to the dark sector? Currently, the explorations by [20, 21, 22] show that there is quite a broad window for new gravitational-strength dark sector forces to operate in, allowing for differences of the order of tens of percents. In the language of dark charges, that translates to the statement that about a third of dark matter could be charged under a dark $U(1)'$. At present, Kaloper, Padilla and Saffin are studying how to generate such a charge asymmetry dynamically, in a cosmological model where during inflation the gauge symmetry is weakly broken. It turns out that the generation of a real nonzero net charge is inconsistent with restoring the symmetry after inflation, essentially because of the Gauss law. As long as the late time $U(1)'$ reduces to the Maxwell's form, with the unbroken gauge symmetry and therefore conserved current, there can't be any nonzero charge. However, it is possible to generate a charge *separation*, because different gauge violating sectors during inflation may decay into different charged particles after inflation ends, which can 'condense' into structures such as galaxies at a different rate. In such a setup, one would end up with a late universe where there may be extra long range forces between cosmological condensed structures.

Finally, Kaloper is interested in the phenomenological implications of dark matter with long range forces of strength comparable to gravity on the large scale cosmology, such as structure formation, imprints on the CMB and so on. Kaloper and Padilla have been collaborating with Anne Green and her student Morris (Nottingham) on the investigation of the cosmological effects of such models. Preliminary investigations show that the extra force could contaminate the Type IIa supernovae Hubble diagram, contributing to the equation of state of dark energy parameter, and it will be interesting to determine precisely the magnitude of these effects consistent with the bounds on extra forces in the dark sector, currently allowed to be around 10% of gravity (implying that about 30% of dark matter may be subject to an extra $\mathcal{O}(1)\times$ gravity long range force) [21, 23].

Exploring modifications of gravity to attack the cosmological constant problem

A possible way around the cosmological constant problem may be to change gravity in the far infrared. If gravity is weakened at such large scales, this weakening of the gravitational impact of a very homogeneous distribution of energy in the Universe may lead to cosmic acceleration. Kaloper, along with Sandora, has been exploring a new model based on extended gravitational Lagrangians, including Gauss-Bonnet terms and higher-derivative scalars coupled to check their consistency with experimental bounds on gravity. Kaloper is also beginning to explore the new developments in the so called massive gravity models [24], which have been proposed recently as a candidate for a consistent framework for the description of five propagating spin-2 massive modes, that avoid the Boulware-Deser ghost problem. Currently, Kaloper, in collaboration with Sorbo and Park (U. Mass, Amherst) is looking for exact shockwave solutions which will test the properties and the consistency of these theories on nontrivial, Lorentz symmetry-breaking backgrounds. Afterwards, if these models pass the consistency tests, Kaloper intends to seek a way of embedding the self-tuning vacuum energy adjustment mechanism in the framework of bigravity [25].

Observational bounds on graviton mass

The recent progress in formulation of massive gravity [24], and massive multi-gravity [25], has led to a conclusion that the classical Pauli-Fierz theory can be fully nonlinearly completed while preserving diffeomorphism invariance and avoiding the Boulware-Deser ghost problem. In these theories, the massive multiplet propagates only the five massive modes, while the sixth mode remains decoupled. In a sense, such a possibility has been indicated earlier [26], however an explicit realization was only developed in the last couple of years. There has already been quite a bit of phenomenological investigation of massive gravity, where researchers mostly assume that the mass of the massive tensor can be as low as the current Hubble scale, $\sim 10^{-33}$eV, which opens up the possibility for searching for the signatures of the extra massive modes at very large scales in the universe. Classically, this remains consistent with the experimental bounds on the modification of Newton's law [27] from table top experiments. However, quantum mechanically the story changes rather dramatically. While the full quantum theory of massive gravity is still not developed, one nevertheless expects that leading order effects can be studied using effective field theory methods. Thus ignoring the issue of the sixth mode's absence, or resurrection, with quantum effects included, we can calculate the correction to the Newton's law from the exchange of the extra helicities present in the theory. In particular, around the usual Minkowski background, because of unbroken local Poincare invariance, the most important corrections come from the helicity-0 mode, whose effective action looks like the action of a scalar field with 'disformal' couplings [28, 29], and whose one loop diagrams induce a correction to the Newton's law scaling as $\Delta V \sim \frac{M_1 M_2}{\Lambda^8 r^7}$ [29]. One can see this result as a consequence of an analogue to the Goldstone equivalence theorem in massive gravity, following from the coupling $\frac{1}{\Lambda^4}\partial_\mu\phi\partial_\nu\phi T^{\mu\nu}$. Here Λ is a mass scale which represents a convolution between the Planck scale, the graviton mass and environmental factors coming from Vainshtein shielding. Because of very fast growth at short distances, this correction can compete with the leading order $\sim G_N M_1 M_2/r$ terms, and place a strong bound on Λ, and so on the graviton mass. With Burrage and Padilla (Nottingham University), Kaloper is finding that the bounds are generically of the order of milli-eV, although there are special regions in the parameter space where the mass can be smaller, but still much larger than the present Hubble scale.

On the Partonic Description of a Black Hole, its Entropy and Temperature

On a more speculative note, Kaloper is curious about looking for more evidence for a partonic description of black holes. Given the renewal of interest in the search for a microscopic description of black hole structure away from the extremal limit [30], this may be a timely exercise. The idea which Kaloper wants to pursue is that a highly boosted black hole can be viewed as a swarm of super-Planckian momentum partons, using nothing more than standard General Relativity of gravitational fields objects with extremely large momenta [31]. In this picture, even though the black hole geometry is obfuscated by the Lorentz contraction, the horizon persists as a latent property of the configuration, revealed in collisions with captured probes [32]. It is the critical value of impact parameter at which the transverse momentum transfer is comparable to the longitudinal momentum, such that the colliding objects equipartition the total momentum between them. This prevents their escape from the black swarm by quantum smearing from the uncertainty principle, and yields the lower bound on the momenta of the constituent partons, given by the Planck scale. The entropy of the black hole counts all the initial conditions that result in probe captures by the swam. Microscopically, it is the number of all possible partitions of the total momentum of the swarm between the constituent partons with super-Planckian momenta. It scales precisely as the black hole area in Planck units. Any allowed partition of the momentum between constituents is a distinct black hole microstate. Their multiplicity can be used to define the statistical distribution of microstates in the black hole configuration, and compute the mean energy of the ensemble. After boosting down to the black hole rest frame, it reproduces the black hole Hawking temperature.

3.6.3 Knox: Cosmological Phenomenology

We propose an investigation of beyond-the-standard-model extensions including extra light and dark particles (such as sterile neutrinos or axions), unstable dark relics, dark matter annihilations and early dark energy. Our main goal is to elucidate the physical reasons for the constraints that data provide, allowing them to be understood in a model-independent manner. Such understanding is invaluable for the rapid exploration of theoretical ideas, as well as the stimulation of new ones. Observables to be used include light element abundances, CMB anisotropy, distance ratios from the acoustic feature in galaxy correlations, H_0 determinations, galaxy cluster abundances and counts of gamma ray events observed by *Fermi*.

Professor Knox's support for his work on *Planck* will ramp down as the mission ramps down, ending in September 2014. During that time, we propose to ramp up Knox's B2 activity, with support for a graduate student starting in Year 1 and summer salary starting in Year 2. He will continue to work on the analysis of data from the South Pole Telescope (SPT) and is proposing to join Task T. For these reasons, his ramp up on DoE Task B2 activities is to 3/8th of "full time, " as reflected in the summer salary request. The proposed work here, while different from that supported by *Planck* and SPT, benefits from years of experience with the interpretation of cosmological data.

Reconstructing the pre-Recombination Universe

The hint of extra neutrino species indicated by a deficit of small-scale power in the cosmic microwave background (as well as revisions of inferences of primordial Helium from observations of extragalactic HII regions, loosening BBN upper limits on the number of neutrino species) has served to highlight that there is plenty of "room" in the pre-recombination Universe for departures from the standard cosmological model, as well as the exciting prospect of discovering those departures with improvements in data. Other theorized departures include long range forces in the dark sector (investigated by Kaloper and collaborators as described above), mirror dark matter [33], massive dark particles that decay to dark radiation [34], energy injection from annihilating dark matter sufficient to observably alter the ionization history through recombination [35], axions and moduli arising in string/M-theory [36] and periods of domination by the potential energy of a scalar field

[37], so-called early dark energy.

Tools for analyzing data to estimate model parameters or discriminate between models are now quite standard, to the point that the parameter estimation process can be a black box into which a parameter model space and some data are thrown and results come out. Extracting a physical understanding of the results is more challenging. Navigating the great variety of theoretical possibilities requires, or is at least greatly aided, by such understanding. **We propose to develop an analytic and model-independent understanding of how cosmological observables are informing us about processes occurring in the pre-recombination plasma.** Much work along these lines already exists, as the general theory of CMB anisotropies was rapidly developed in the time following the *COBE* detection of anisotropy in 1992 and into the first few years after the *WMAP* launch. We plan our work to be done, in contrast, in the context both of the actual current measurements in hand and current theoretical ideas for departures from the standard cosmological model.

Before moving on to some specific projects in this theme, we review some relevant completed work. There has been great interest recently, for a number of independent reasons (a deficit of high-l CMB power, reactor neutrinos, short baseline neutrino oscillation experiments, new inferences of the amount of primordial Helium, see [38] and references therein) in the possibility of extra species of neutrinos. We demonstrated in [38] that the mechanism by which neutrinos suppress high l power was quite simple and dependend entirely on the neutrino's contribution to the expansion rate, and the differing dependences of the sound horizon and photon diffusion scale on expansion rate. Although this particular mechanism was already described in the literature [39], so were others because neutrinos also influence the CMB through the impact of their perturbations on the metric, and through the early ISW effect. We showed that these other effects are unimportant for understanding constraints from current data.

Given the sensitivity of the CMB power spectrum to the expansion rate, in the case of variable number of neutrino species, it is natural to ask **how well can we constrain the expansion rate in a more model-independent manner?** We note that the massless neutrino case studied so far is a special case because changing the expansion rate in this way does not change the shape of $H(z)$ but only its amplitude. One might think it *would* change the shape, by shifting the redshift of matter-radiation equality, but the CMB anisotropy is very sensitive to $z_{\rm EQ}$, so in practice if there are extra neutrinos there is extra dark matter also to keep $z_{\rm EQ}$ fixed.

But what about adding in components that do not redshift like either matter or radiation? First off, doing so means $z_{\rm EQ}$ is no longer well-defined. So what aspect of the expansion history remains well-determined more generally? Given the sensitivity of the CMB to $z_{\rm EQ}$, are other components strongly constrained? What constraints can be put on a component with an equation-of-state that has it redshifting more slowly than radiation, but more rapidly than matter? How do we understand the constraints that can be placed on early dark energy [40]?

We plan to proceed by gaining understanding of particular cases, modifying publicly available Einstein-Boltzmann solvers and exploring the parameter constraints with the Monte Carlo Markov Chain technique. Understanding how the data lead to constraints on the expansion rate in these particular cases will allow us to then generalize (to the extent possible).

Another reconstruction-type question we will address is **what do CMB data tell us about the transition from a completely ionized Universe to a nearly neutral one?** The agreement between predictions of CMB anisotropy power spectra and precision observations of the damping tail region of that spectrum indicate that we have correctly modeled the ionization history as it transitioned from complete ionization to nearly neutral around a redshift of about 1100. But how well do data actually constrain the ionization history? If we were to treat the mean ionization fraction as a free function of redshift, how well could we reconstruct it from the data? What aspects of that reconstructed $x_e(z)$ would be well determined? In this light, **what can we say about potential sources of energy injection into the plasma from, e.g., dark matter annihilation?**

We have partially pursued this question. Our approach is to parameterize departures from a fiducial, physical $X_e(z)$ as a piece-wise continuous function specified at a set of control points z_i. Then, via a Fisher matrix analysis, assuming a given set of observations we perform a principal component decomposition to separate the variations of $X_e(z)$ into a set of modes, ordered by how well the data can constrain them. We will then estimate the amplitudes of the best determined modes by an MCMC analysis, marginalizing over the cosmological parameters. A similar approach to reconstructing the ionization history at low redshift, through the process of reionization, was presented by Hu & Holder (2003). See Fig. 20 that shows the first few eigenmodes as well as the eigenvalue spectrum.

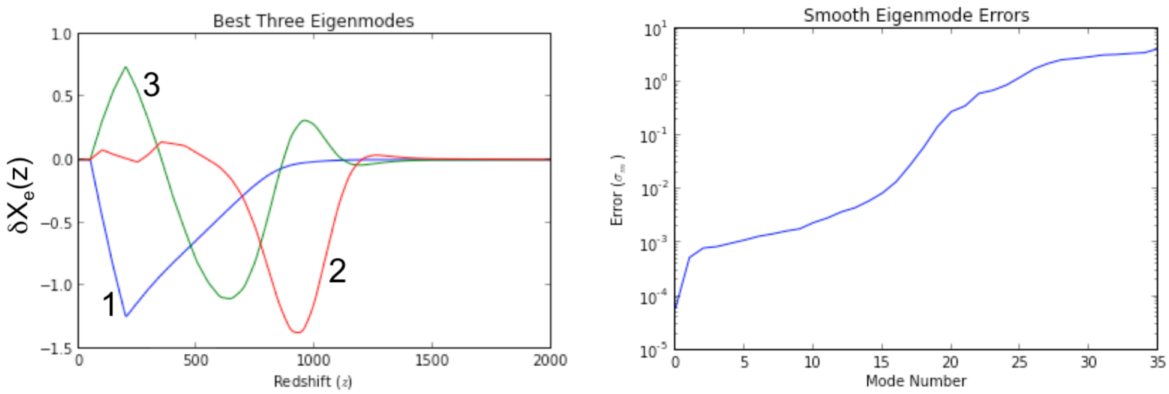

Figure 20: First few eigenmodes of $X_e(z)$ (left panel) and the errors for the complete spectrum of modes (right panel), for *WMAP*7 + SPT power spectra. ¿From this spectrum of modes we learn in a model-independent manner what properties of $X_e(z)$ can be determined well from the data. The eigenmode with the lowest eigenvalue has a shape particularly well-matched to signals expected from low-mass cold dark matter [35].

As pointed out by [35] the low-mass (5-10 GeV) dark matter models invoked to explain possible direct detections [41] are expected to generate signals large enough to be detected in *Planck* data. While [35] found that *Planck* would be sensitive to five different principal components of the energy injection history, we see here that even with just the *WMAP*7 + SPT data that we are sensitive to a wider variety of signals, with about 25 modes whose amplitudes can be measured with signal-to-noise greater than 1. Our less model-dependent analysis widens the scope of possible discoveries.

From BBN to Recombination

We are particularly intrigued by the power of joint analyses of light element abundances and CMB anisotropy data to discover or constrain exotic processes. **We propose to search for indications of new physics from the combination of CMB observations and light element abundance measurements.** We will collaborate with Professor Brian Fields (UIUC), a BBN expert. We will leverage the work being done at UIUC to develop a framework that allows for a joint analysis of BBN-related data and CMB data that rigorously and efficiently propagates the uncertainties in nuclear reaction rates. We have a consulting role in this project, supported by a small subcontract with UIUC that supports (only) travel between Davis and UIUC.

The observational situation is now quite exciting. New CMB data will soon increase the precision on estimates of the baryon density, $N_{\rm eff}$ and $Y_{\rm P}$. In addition there is a recent inference of D/H from a very clean quasar absorption line system [42], with errors about 3 times smaller than previous ones. In Fig. 21 we show constraints from $Y_{\rm P}$ and D/H measurements on ω_b and $N_{\rm eff}$ (tighter contours) and for the same quantities from CMB data (looser contours). For the latter we allowed $Y_{\rm P}$ to be a free quantity; i.e., we made no assumptions about BBN so that the two sets of inferences are completely independent.

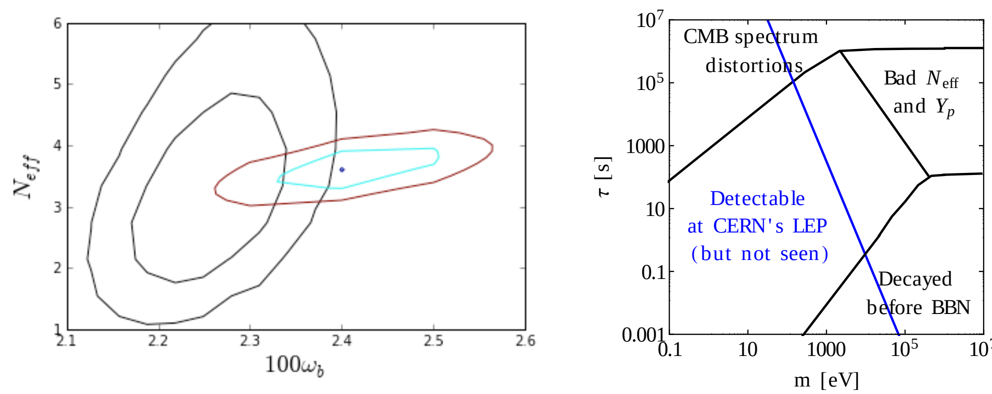

Figure 21: Left panel: Sixty-eight% and 95% confidence contours inferred from light element abundance data (tighter contours) and CMB data (looser contours). As new data lead to tighter contours, we may get inconsistent results pointing to new physics. Right panel: A preliminary analysis of constraints on a hypothetical particle radiatively decaying after big bang nucleosynthesis. "Bad $N_{\rm eff}$ and $Y_{\rm P}$" means inconsistent with those values as inferred from CMB power spectrum observations. "Decayed before BBN" indicates a region that remains viable because there are no observable consequences of such decays. Note that at the edge of this boundary there is a region of "during BBN decay"(not indicated) whose consequences are more challenging to calculate. The LEP bound we calculated based on the lack of a resonance in e+/e- scattering, and an assumed interaction Lagrangian for the χ particle of $1/M\chi F^2$ where F is the electromagnetic field strength tensor and M is a mass scale which can be determined as a function of τ and m. "CMB spectrum distortions" labels the region that would induce a photon chemical potential in excess of the bounds from *COBE*/FIRAS.

We will look for new physics by exploring results from a series of modeling assumptions and data sets. With tighter assumptions, we can afford more data editing. For example, if we assumed $\omega_b^{\rm BBN} = \omega_b^{\rm DEC}$ (where DEC stands for decoupling of photons and baryons; i.e., what is inferred from CMB data), then we no longer need to include the inferences of $Y_{\rm P}$ and can still infer $N_{\rm eff}^{\rm BBN}$ (from D/H and CMB data) while allowing $N_{\rm eff}^{\rm BBN}$ to differ from $N_{\rm eff}^{\rm CMB}$.

The $\omega_b^{\rm BBN} = \omega_b^{\rm DEC}$ assumption is consistent with processes that change $N_{\rm eff}$ between BBN and decoupling, but that leave the baryon-to-photon ratio (expressed as ω_b) unchanged. This situation would result from the scenario proposed by [34] where a dark massive unstable particle decays, after BBN, into dark but light particles, thereby increasing $N_{\rm eff}$.

Another general possibility is the relation $\omega_b^{\rm DEC}/\omega_b^{\rm BBN} = \left(N_{\rm eff}^{\rm DEC}/N_{\rm eff}^{\rm BBN}\right)^{3/4}$ which one gets if both the neutrinos and the baryons are diluted by energy injection into the plasma after neutrino decoupling. With the new D/H data, we suspect the bounds on any change in $N_{\rm eff}$ would be quite tight, certainly tight enough to rule out the axion-cooling solution to the lithium problem proposed by [43].

General relations are of interest for their broad applicability. But given a specific scenario, more information can be brought to bear. We have performed a preliminary analysis of a specific scenario satisfying the above relation, where the energy injection is from an unstable particle that is nonrelativistic during BBN. Results of our preliminary analysis, which we propose to extend and complete, are shown in the mass-lifetime plane in Fig. 21.

Detecting Dark Matter in Fermi Data

If the cold dark matter is a thermally produced relic of the Big Bang then its annihilation cross section may very well be large enough that annihilations in the galactic center, Milky Way subhalos and extragalactic dark matter halos may all contribute significantly to gamma ray signals in *Fermi* data. In addition to potentially producing detectable line emission, there can also be continuum emission from a variety of processes including the decay of pions that form from hadronization of quarks and inverse Compton scattering of background photons by charged decay products. Definitively detecting such a signal would, of course, be a remarkable achievement, giving us information about the mass of dark matter and some indication about the annihilation cross section.

The large-scale isotropic diffuse gamma-ray background (IGRB) measured by *Fermi* may very well contain these signals, but disentangling them from astrophysical sources of gamma rays is a great challenge. Contributions are expected from unresolved members of several established astrophysical gamma-ray source classes [44]. Interestingly, recent results suggest that only ∼15-25% of the IGRB is composed of emission from the unresolved partners of these observed sources [45], leaving open the possibility that much of it is from dark matter annihilation.

Conventional approaches to discriminating between different components of the IGRB are hindered by their reliance on prominent spectral features and on accurate modeling of the primary contributors. To supplement these methods, recent work has considered angular fluctuations in the IGRB from various unresolved source populations (e.g., [46]) and as a function of energy, $C_l(E)$ [47].

As helpful as $C_l(E)$ is, it is missing a huge amount of valuable information – that contained in the off-diagonal terms. **We propose to include this information in a hunt for dark matter in the *Fermi* maps.** To understand the power of the off-diagonal terms, consider that if we take 7 energy bins from 0.5 to 50 GeV means then there are 7 $C_l(E)$ compared to 28 total $C_l(E, E')$. One now has sufficient constraints to, in principle, disentangle up to 4 components, even with the energy spectrum of each component completely free (so defined by 7 parameters). Here we have implicitly assumed that the components have spectra that do not vary spatially, and that the components are not spatially correlated with eachother. These assumptions can be dropped, in favor of other ones such as power laws for the spectra of some of the sources. The point is that there is a lot of information in the off-diagonal terms that no one has yet used. The closest prior work in the literature is [48], but this still does not fully exploit all the available information, and is not an analysis of *Fermi* data.

Our analysis will substantially increase our knowledge of unresolved source populations, addressing the single-most important barrier to detecting dark matter with the IGRB. The Fermi LAT data are publicly available as a list of photon events. We will bin them into Healpix map pixels and use standard power spectrum analysis tools in collaboration with J. Siegal-Gaskins who is a member of the *Fermi* team (see letter of commitment in an Appendix).

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3.7 B2 Task Personnel

6-a PI's

1. **Andreas Albrecht**, Full Professor, PhD from University of Pennsylvania, research interests in inflation, early universe cosmology, holographic principle, dark energy, arrow of time.

2. **Nemanja Kaloper**, Full Professor, PhD from University of Minnesota, research interests in inflation, early universe cosmology, particle physics, black hole physics, dark energy.

3. **Lloyd Knox**, Full Professor, PhD from University of Chicago research interests in inflation, early universe cosmology, astroparticle particle physics, observational cosmology, dark energy.

6-b Junior researchers with partial support explained

In addition to the PI-s, Task B2 has supported during the review period, or will support:

1. **Two postdoctoral fellows** This proposal lists two future postdoctoral fellows (fully DOE supported), to be jointly recruited and mentored by the three PI's. As discussed in the *Task B2 Mentoring* section of this document the three PI's have an excellent track record of successfully mentoring junior researchers together.

2. **Five graduate students** This proposal lists five future graduate students, to be shared among the three PI's roughly in proportion to their % effort on this grant (100% for Kaloper and Albrecht, and 3/8 for Knox (years 2-4). This will allow us to support more than this number of students by using partial TA support. As discussed in the *Task B2 Mentoring* section of this document the three PI's have an excellent track record of successfully mentoring junior researchers together.

3. **Norihiro Tanahashi** Postdoctoral Fellow (Full DOE support at UC Davis through August 2013), PhD from Kyoto University (Japan), research interests in early universe cosmology, gravity, black hole physics.

4. **Minjoon Park** Postdoctoral Fellow (Combined DOE and UC Davis support, at UC Davis through August 2009). Moved in 2009 to a postdoc at U. Mich. and now U. Mass. Amherst.

5. **Alberto Iglesias** Postdoctoral Fellow (Full DOE support at UC Davis through August 2013),

6. **Augusta Abrahamse** (Albrecht 2010 PhD graduate, partial DOE support, some support from Knox research grant, otherwise supported by TA positions. Currently a Lecturer at Universidad Privada Boliviana)

7. **Brandon Bozek** (Albrecht 2009 PhD graduate, partial DOE support along with TA support. Currently a postdoc at JHU)

8. **Aaron Hernley** (Albrecht PhD student, partial DOE support along with TA support)

9. **Dan Phillips** (Albrecht PhD student, partial DOE support along with TA support)

10. **McCullen Sandora** (Kaloper PhD student, partial DOE support along with TA support)

11. **Andy Scacco** (Albrecht/Kaloper PhD student, partial DOE support along with TA support)

12. **Andrew Ulvestad** (U. Chicago PhD student who collaborated with Albrecht during Albrecht's 2010-2011 sabbatical at U. Chicago. One quarter of DOE support in 2011)

13. **Nadia Bolis** Started our PhD program in fall 2011, decided to pursue cosmology and won an NSF Fellowship Honorable Mention (despite lack of prior cosmology experience and a full load of first year classes). Plans to work with Albrecht and clearly a candidate for future DOE support.

4 Tasks C and L: Neutrinos and Dark Matter

4.1 Project Overall Objectives

The Neutrino and Dark Matter Group at UC Davis has two major scientific goals:

- Investigate the nature of the neutrino by determining the ordering of the masses, the pattern of flavor mixing, and whether they might be the origin of the baryon asymmetry of the universe by violating CP symmetry.
- Determine the nature of the astrophysical dark matter that dominates the matter density of the universe by directly detecting it in the lab, measuring its mass, and investigating its interaction properties.

During the period of this grant, our group is involved in two active experiments, LUX and Double Chooz (DC). DC has been taking neutrino data since 2011 with the Far Detector only, while LUX has finished detector commissioning and is now taking science data underground. We will report on the results from DC single detector operations and LUX commissioning and initial detector performance. The role of our group in realizing these results will be detailed, and the timeline for achieving additional new results will also be presented.

4.2 Project Personnel 2010-2013

The Neutrinos and Dark Matter Group is intellectually one coherent group working on both Intensity Frontier and Cosmic Frontier projects. Although FTE levels and budgets are reported individually, it is more appropriate to report accomplishments coherently, as people are often split. For example, Szydagis is an expert in noble gas detector simulations so it is natural that he is a convener for the simulation groups for both LUX and LBNE. Table 1 is a list of group members and the projects they worked on during this period.

4.3 Task C: Double Chooz and LBNE (Intensity Frontier)

4.3.1 Double Chooz

During the period of this grant, the UC Davis Group has been working on the construction of the Double Chooz reactor neutrino experiment, with the goal of measuring the neutrino mixing angle θ_{13}. Our main construction responsibilities included:

- Responsibility for Radiological Cleanliness during construction (Completed)
- Construction and installation of the Far Detector Calibration Glove Box and associated gas system and detector isolation valve (Completed)
- Participation in the design, construction, and operation of the Far Detector scintillation filling system (Completed)
- Design and construction of the Articulated Arm (used to position sources) enclosure and gas system (Completed)

Name	position	experiments	comment
Robert Svoboda	professor	LBNE, DC	
Mani Tripathi	professor	LUX, LZ	
Marc Bergevin	postdoc	DC	
Chris Grant	postdoc	DC	
Tim Classen	postdoc	DC	left 12/11
Rich Ott	postdoc	LUX	
Matthew Szydagis	postdoc	LUX, LBNE	
Morgan Askins	grad student	LBNE	left LBNE for another project
Justin Dhooghe	grad student	DC	
John Felde	grad student	DC	will graduate 8/13
Chad Flores	grad student	LUX, LZ	
Matt Lawson	grad student	TBD	
Cara Maesano	grad student	DC	graduated 12/12
Jememy Mock	grad student	LUX	
James Morad	grad student	LUX, LZ	
Sergey Uvarov	grad student	LUX	
Nick Walsh	grad student	LUX/DC	
Mike Woods	grad student	LUX	
Hans Berns	engineer	LBNE	

Table 1: The Neutrino and Dark Matter Group at UC Davis. Personnel in this table all received some fraction of support from this grant. Other sources included: (i) Teaching Assistantships, (ii) Work-Study Fellowships, (iii) UC Davis Black Grant, (iv) NSSC Training Fellowships.

Currently, the Glove Box for the Near Detector is still under construction, to be completed by the end of CY 2013.

θ_{13} **Measurements:**The Double Chooz Far Detector began taking data in April 2011, following a successful filling and commissioning operation. We published our first results on θ_{13} in November, 2011 using 96.8 days of reactor on livetime and a Far Detector only [52]. In this paper, both the measured rate and spectral shape of antineutrinos was compared to an empirical model of reactor flux [53] based on beta spectrometry data [54] to extract the value of θ_{13}: $\sin^2(2\theta_{13}) = 0.086 \pm 0.041(stat.) \pm 0.030(syst.)$ This result confirmed the hint from the T2K experiment that θ_{13} was large [55], and was the first of a new generation of reactor experiments designed to measure this parameter. In 2012, further confirmation came from the Daya Bay [56] and RENO [57]

[52] Y.Abe *et al.* [Double Chooz Collaboration], "Indication for the disappearance of reactor electron antineutrinos in the Double Chooz Experiment," Phys.rev.Lett. **108** 131801 (2012)

[53] Tomas Mueller, Ph.D. Yhesis Saclay (2010)

[54] K.Schreckenbach *et al.*, "Determination of the antineutrino spectrum from ^{235}U thermal fission products up to 9.5 MeV," Phys. Lett. B **160** 325 (1985)

[55] K.Abe *et al.* [T2K Collaboration], "Indication of electron neutrino appearance from an accelerator-produced off-axis muon neutrino beam," Phys. Rev. Lett. **107** 041801 (2011)

[56] F.P.An *et al.* [Daya Bay Collaboration], "Observation of electron antineutrino disappearance at Daya Bay]," Phys. Rev. Lett. **108** 171803 (2012)

[57] J.K.Ahn, et al. [RENO Collaboration], "Observation of electron antineutrino disappearance in the RENO experiment," Phys. Rev. Lett. **108** 191802 (2012)

experiments.

Following the first publication we worked to reduce the systematic uncertainties by reducing backgrounds and getting a better understanding of their spectral shape. At the Neutrino 2012 conference in June, 2012 we updated our result to 227.9 days and presented results from our improved analysis. [58] The new spectrum is shown in figure 4.3.1. The new best fit value was $0.109 \pm 0.030(stat.) \pm 0.025(syst.)$ with an excellent $\chi^2/DOF(= 41.1/35)$. In addition, The systematic uncertainties are significantly reduced ($4.3\% \rightarrow 2.7\%$) due to better understanding of the energy calibration, the installation of an Outer veto (OV) system, and a tighter cut on ^{9}Li cosmogenic backgrounds.

In 2012, we took advantage of the fact that the Double Chooz "Gamma Catcher" (GC) volume surrounding the Neutrino Target (NT) has mass of 18 tons, as compared to 8 tons in the target itself. Consequently, it is possible to make an independent determination of $\sin^2(2\theta_{13})$ using the GC. In this case, the neutrons from the Inverse Beta Decay (IBD) antineutrino interactions are captured on hydrogen instead of gadolinium, and so constitute an independent data set from the NT events. While backgrounds are higher, due to less shielding, the result is comparable due to the larger mass. The result (recently accepted for publication in Physics Letters B) is $0.097 \pm 0.034(stat.) \pm 0.034(cyst.)$. Currently, we are working on combining these two independent data sets into a single result, taking into account correlations in signal extraction, calibrations, and background determination. These results will be presented at conferences starting in August, 2013, to be published soon after.

It is interesting to compare the setups of the three running reactor experiments. While Double Chooz has smaller detectors than Daya Bay or RENO, it has two very unique features: (1) we do get time periods when one or both reactors are off, allowing us to measure backgrounds with high confidence, and (2) the Far and Near detectors are situated such that the ratio of the distances from both cores to the two detectors are very nearly the same. Thus there will be essentially **no** correction for the individual core fuel loading and power level. This is very important in getting a good spectral shape when fitting to neutrino oscillations. Thus, after the Double Chooz Near detector starts running it will take a while to get statistics due to the small size, but eventually when systematics take over these advantages will make the Double Chooz spectral shape measurement unique and competitive. Indeed, only Double Chooz has published a shape+rate result. In addition, we are the only reactor experiment that has directly measured their backgrounds using reactor off data.
[59]

Activities of UC Davis Personnel: In addition to participation in detector construction and data analysis, there were several aspects that can be separated out as being specific to UC Davis only. In two cases (Maesano and Felde) these were analyses used for their PH.D. thesis.

Stopped Muon 9-Li Analysis (Maesano, Svoboda): The major background for Double Chooz is cosmogenic ^{9}Li due to the long lifetime and ability to mimic reactor neutrino events. It is known that muons accompanied by large hadron showers show enhanced production, presumed to be due to

[58] Y.Abe, *et al.*[Double Chooz Collaboration], "Reactor electron antineutrino disappearance in the Double Chooz Experiment," Phys.Rev. D **86** 052008 (2012)

[59] Y.Abe, *et al.* [Double Chooz Collaboration], "Direct Measurement of Backgrounds Using Reactor-off Data in Double Chooz," Phys.Rev. D **87** 011102 (2013).

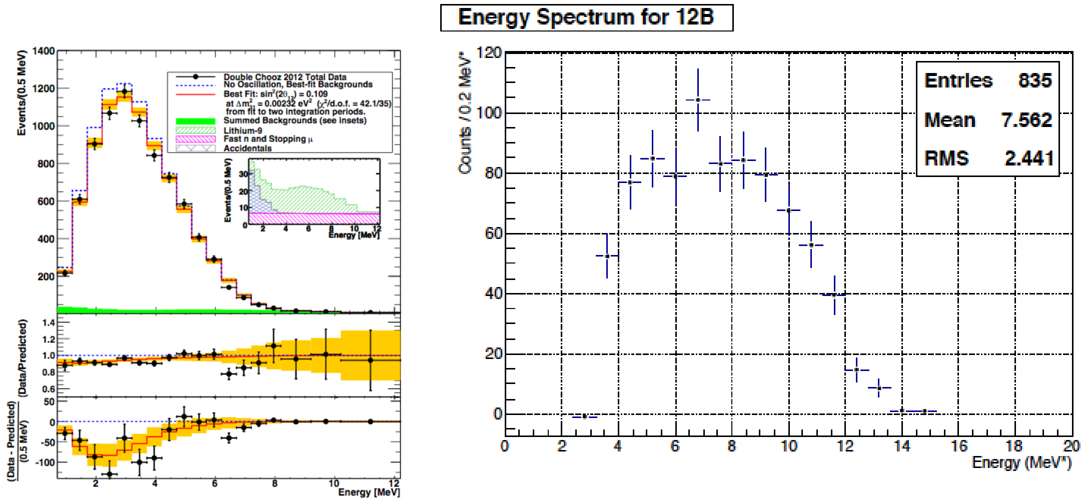

Figure 22: The spectrum and oscillation fit from the Run 1+2 228 day sample (left). Background subtracted 12-B spectrum from the UC Davis analysis (right).

nuclear breakup from DIS and/or π^- capture [60]. This drives the cuts used to reject ^{9}Li events to showering muons. It is in principle possible however, for μ^- capture on ^{12}C to also transfer large amounts of energy to the parent nucleus, resulting in similar breakup. Naively, one might think that the vast majority of the energy would be carried off by the neutrino daughter in the reaction: $\mu^- + p \rightarrow \nu_\mu + n$, $(E_\nu = 99.1\ MeV)$, but this is manifestly incorrect. In reality nuclear effects are very large, such that in carbon only 18.6% of captures go to a bound state of ^{12}B, the rest leading to nuclear breakup. UC Davis student Cara Maesano, has investigated this possible process as her thesis topic. The strategy for this analysis was to measure the rate of ^{9}Li production per stopped muon as compared to the well-measured ^{12}B production rate. This is possible since both isotopes have a similar Q-values (13.6 vrs 13.4 MeV) and log(ft) values for their major branching ratios (5.1 and 5.5 vrs 4.1), and thus have similar detection efficiencies requiring only small corrections. To do this measurement, a sample of "captured" muons was produced by identifying stopped muons with no observed Michel electron. Figure 4.3.1 shows the spectrum of the background subtracted ^{12}B candidates in this sample. The measured rate is $8.60 \pm 0.37\ d^{-1}$, close to our original 10/day estimate. The background (about 25% of the sample) was measured by using an off-time window. We then searched for ^{9}Li events within 0.95 seconds (3.7 ^{9}Li lifetimes) of a captured muon, but found none above background. By correcting the ^{12}B rate for the energy threshold and time cuts, a 90% c.l. limit of <3% ^{9}Li per captured muon was set on ^{9}Li production. Masesano graduated in July, 2013.

Neutron Multiplicity Study (Bergevin): In Double Chooz, the target nuclei for neutron capture are ^1H, ^{157}Gd and ^{155}Gd. The published Double Chooz analysis concentrated only on neutron capture with the Gd isotopes since they are contained in a target acrylic vessel and this creates a natural fiducial volume. UC Davis studies were key in the evaluation of this detection efficiency. Studies were completed with ^{252}Cf to understand the time and energy response of the detector to neu-

[60] S.Abe, *et al.* [KamLAND Collaboration], "Production of radioactive isotopes through cosmic muon spallation in KamLAND," Phys. Rev. C **81** 025807 (2010)

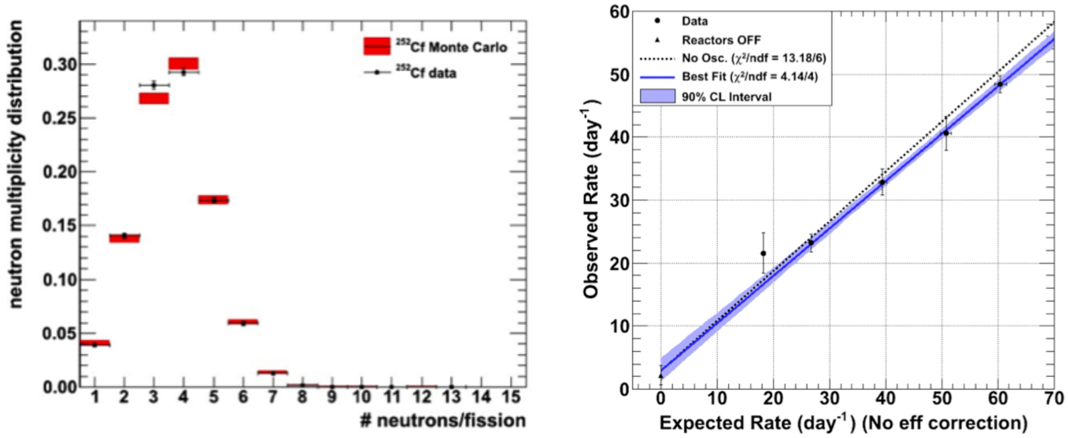

Figure 23: Neutron multiplicity distribution of ^{252}Cf source for the Double Chooz experiment compared to Monte Carlo (left). Result of John Felde's reactor power analysis for θ_{13} (right).

trons. The signature of ^{252}Cf is a prompt cascade of fission gammas followed by multiple delayed neutrons. The study of the neutron capture time structure showed no trigger time anomalies. In addition, measuring the neutron capture efficiency via detected neutron multiplicity can be directly benchmarked against values published in the literature. Figure 4.3.1 shows the multiplicity distribution of all neutrons captures (Gd plus H). Separating the 2.2 MeV H capture events from the 8 MeV Gd capture events by requiring E>6 MeV gave the neutron detection efficiency 86.0% used in our publication. It was also used to tune our Monte Carlo. Further studies of neutrons are continuing with the new ^{252}Cf data from the recent calibration campaign and the study of fast muon-induced neutrons. Note: Bergevin will complete Double Chooz work by the end of 2014.

Independent θ_{13} Analysis (Felde, Svoboda): In the published first data analysis our collaboration agreed to use the full-power value for the systematic error associated with the reactor thermal power (0.5%),since this is the case most of the time. However, the relative thermal power error, σ_P/P, is well-known to increase at lower power. To take this into account, we have completed an independent θ_{13} analysis that includes this power-dependent uncertainty. For the published data our independent rate-only analysis yielded a value of $\sin^2(2\theta_{13}) = 0.089 \pm 0.077$ and an estimate of the background rate of $2.91 \pm 1.47\ d^{-1}$ (see figure 4.3.1). We also concluded that the constant value used for the thermal power uncertainty in our first publication is valid given the statistics of that run period. Nevertheless, this work has led to a better prescription for calculating the thermal power errors which was included in the most recent general analysis soon to be published. Recently, both reactors have been shut down simultaneously for a total of 7.53 days. When included, these data will have a significant effect on lowering the error on our independent analysis, which is the subject of Felde's Ph.D. thesis.

Glove Box and Calibrations (Dhooghe, Felde, Grant, Svoboda): The Double Chooz Glove Box (GB) is a vital component for maintaining a pressure-regulated, low-oxygen environment during detector calibrations. Designed, built, and tested at UC Davis, the GB is a stainless steel chamber that provides direct access to the neutrino target and provides an interface to the calibration deployment systems. Safe operation of the GB during calibration deployments is the responsibility of the

UC Davis group. The GB assembly is shown assembled inside the UC Davis built clean tent in figure 24. Major calibration campaigns took place in August 2011 (Felde, Svoboda) and May-June 2012 (Bergevin, Felde, Grant), involving extensive deployments of both radioactive and laser-ball sources on the central axis. During this proposal period we will continue to provide multiple on-site personnel to operate and maintain the GB. In 2012-13 we will be working with ANL/Drexel/Hawaii to modify the existing Far Detector GB with an extension made to allow deployment of the Articulated Arm (AA). This device will allow deployment of radioactive sources throughout the volume of the neutrino target, greatly improving the geometric corrections on the energy estimator and vertex fitter. In addition, in 2013 we will fabricate an identical GB to be installed in the Near Detector. All parts and equipment for this are already in hand.

Service and Other Activities UC Davis fulfilled all shift requirements for Double Chooz, both on and off site. In addition, Chris Grant is in charge of Data Processing for Double Chooz (he will finish this task by the end of 2014, and has now moved 50% of his effort to LBNE). Nick Walsh will complete his analysis of neutron-induced backgrounds and is expected to graduate by the end of 2014. Justin Dhooghe is participating in Near Detector construction and is expected to graduate in 2015. No further graduate students on Double Chooz are anticipated.

Figure 24: The UC Davis GB installed at the Far Detector Lab (left). Happy UC Davis and Univ. of Alabama physicists duriing the 2012 calibration campaign (right).

4.3.2 LBNE

Svoboda served as Co-Spokesperson of LBNE during most of the period of this grant (20010-2012). During this tim, the Conceptual Design Report (CDR) was completed for all three major components of the experiment: (1) Far Detector (FD), (2) Near Detector (ND), and (3) Neutrino Beamline. The CDR lays out the basic requirements and gives the sensitivity, cost range, schedule, and alternatives analysis for use in zeroing in on a final configuration. UC Davis did a considerable amount of work on the Water Cherenkov (WC) option for the FD[61]. The 200 kton WC option was recommended by the LBNE EC, but this recommendation was reversed by the DOE Project Manager who selected a 34 kton Liquid Argon (LAr) TPC. Our group began redirecting effort

[61] This is now documented in arXiv:1204.2295

to LAr technology and ND - hosting an ND workshop in March 2012. LBNE was subsequently downscoped in July 2012 to a 10 kton FD on the surface at Homestake with no ND.

During this critical time, Svoboda served as Co-Spokesperson of LBNE from almost the beginning of the experiment. This last year, he guided the collaboration through a difficult choice of Far Detector technologies, in addition to being a driving force in the "Case Studies" done to prepare for this decision. Last year he also served on the Risk Assessment Board, "Tiger Team" cost re-evaluation effort, and Reconfiguration Steering Committee. He also contributed significantly to the Cosmogenics and Cosmic Ray Working Group study of backgrounds in a surface detector.[62]. In addition, UC Davis worked extensively on the development of the WC option for LBNE, establishing test facilities for both measuring magnetic effects on detector sensitivity and evaluating a prototype for a thin veto around the detector to reject beam-associated "rock muons." In addition, a team of graduate students and postdocs worked on the evaluation of the effects of such muons on the measurement of the basic oscillation parameters. This work has been completed and documented.

One area we have been able to contribute to immediately despite changes in LBNE scope is in the simulation of photon and electron production and transport, since this is very similar to the tools (NEST) developed for LUX. This is described below. We are currently exploring the possibility of using LAr technology to determine muon (and hence neutrino) sign selection via muon capture, although work on this is just starting.

Completion of WC FD work (Bergevin, Breedon, Dhooghe, Felde, Svoboda): This year we completed the measurement and evaluation of the 10" and 12" Hamamatsu PMTs using our specially-built test stand. The efficiency of PMTs can change by as much as 20% in the presence of the earth's field depending on geometry and details of the electron optics, and therefore the effect on the detector performance is twofold: (1) a reduction of overall light collection due to reduced efficiency, and (2) a directional systematic that traces the Earth's field direction with respect to the PMT axis. These results were published in NIM. [63]

Any detector in a neutrino beam will have beam induced muons entering from interactions in the rock. As they are in time with the beam, they cannot be removed by simple timing cuts. Our studies indicate that 29% of all beam associated neutrino events will be rock muons. For the WC option, it was possible that a problematic fraction of these events could be misidentified as being contained if there were no veto on the upstream end of the detector. We therefore built and tested a prototype veto system in 2011-2012 and completed feasibility and cost studies for the CDR. We determined that a simple 85 cm region in back of the PMTs could be instrumented with 2 8-inch PMTs per 10^2 meters to give an efficiency for rejection of >95%. This information will be of use for future large WC detector, and was presented in a talk at the International Hyper-Kamiokande Workshop in Tokyo, August 2012.

Conversion of NEST Software for Use in LBNE:(Szydagis) It is very important for LBNE simulations to have accurate models of the production and transport of electrons and photons. Existing simulations (e.g. LArSoft) have empirical models that are fits to data in the literature rather than comprehensive physical models. The Nobel Element Simulation Technique (NEST) software devel-

[62] "Muon-induce backgrounds for Beam Neutrinos at the Surface", www.fnal.gov/directorate/ see "LBNE Reconfiguration"

[63] J.Brack, et al., "Characterization of the Hamamatsu 11780 12-inch Photomultipler Tube," NIM A 162 (2013).

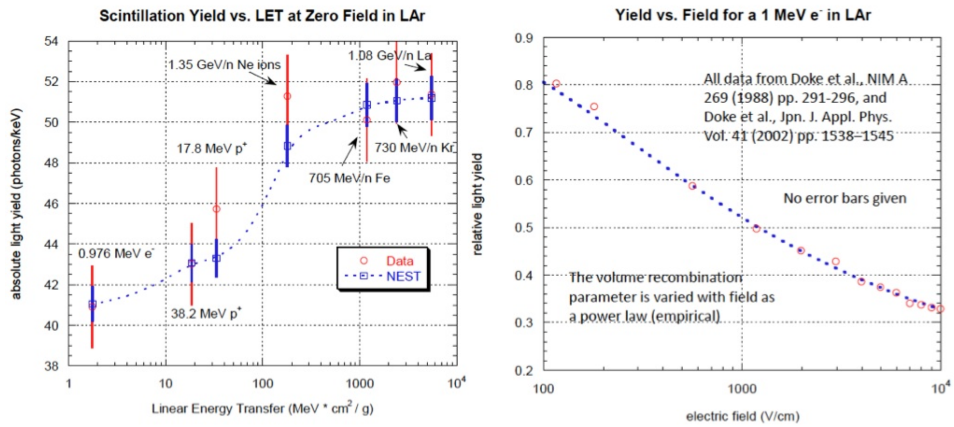

Figure 25: UC Davis simulation using NEST adapted for LAr for LBNE. The scintillation yield versus the Linear Energy Transfer (LET) for zero field data and NEST (left). The relative light yield versus field for data and NEST (right).

oped at UC Davis is a self-consistent physical model based on standard atomic physics enhanced by stochastic processes. It was developed for LUX and liquid xenon, but the model has now been extended by Szydagis (the original creator) to LAr for LBNE. As can be seen in figure 4.3.2, there is a good match of the argon data to NEST. This gives confidence that the behavior of the LAr TPC can be predicted for many different possible combinations of particles. In addition, the anti-correlation of scintillation with charge yield is preserved on an event-by-event basis. This was a major step forward for LBNE LAr simulations and continued work on this will be a major UC Davis contribution in the following years.

In addition, to NEST work, Svoboda and Grant started work evaluating the backgrounds for a liquid argon TPC, both on the surface and underground. This included: (i) calculation of the backgrounds from (n,p) reactions and work on a possible experiment at LANL to measure the cross section for this above 15 MeV, (ii) work on the possibility to improve knowledge of the SN neutrino cross-section by a measurement at SNS, and (iii) work on the requirements for underground facilities for LBNE at SURF. We also participated in all LBNE collaboration meetings and in two Hyper-Kamiokande working group meetings.

4.4 Task L: Direct Dark Matter Searches (Cosmic Frontier)

The LUX detector was assembled in a surface lab at Sanford and was run successfully in 2011-12. This run provided for full commissioning and debugging of various systems, and the detector was then installed underground. Assembly of support services underground progressed rapidly, and a cool-down of the detector was completed in early 2013. LUX, the world's largest dark matter (DM) detector as of now, is now running and collecting data in a Dark Matter search mode. With one year of underground running and a fiducial mass of 100 kg, LUX is projected to have a 90% C.L. spin-independent sensitivity of $3 \times 10^{-46} cm^2$ for a 100 GeV WIMP mass, as shown in Figure 26 (bottom-right). This projection is for a DM search window of 3.4-25 keV nuclear recoil (NR) and 60% acceptance for NR events. It also incorporates a "sub-threshold" analysis, a procedure which

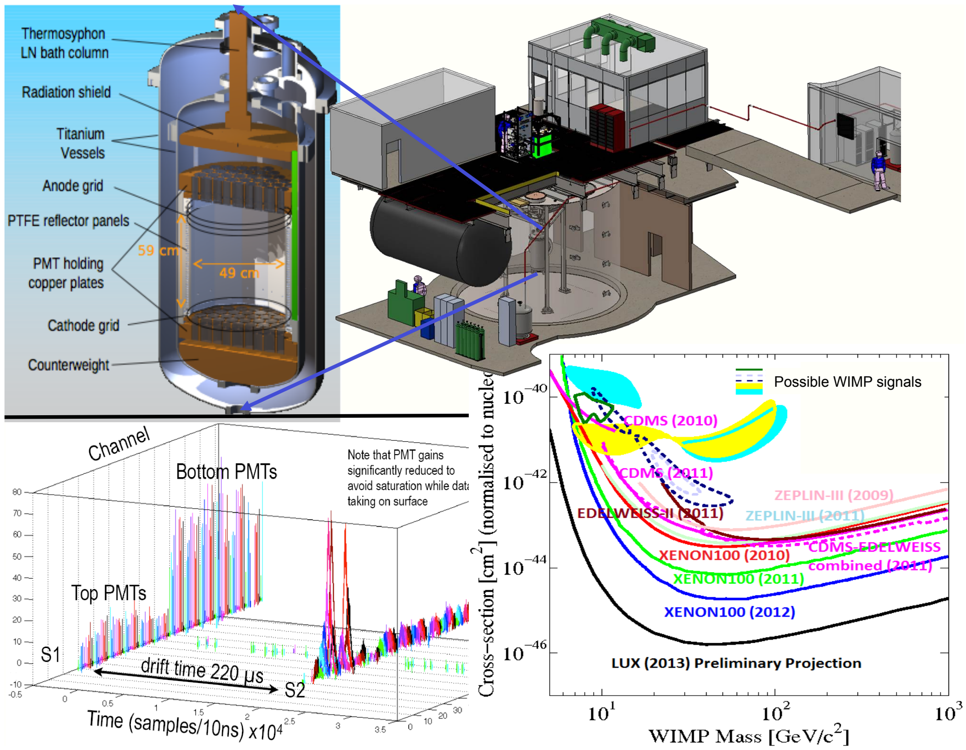

Figure 26: Top left: A detailed design of the LUX two-phase Xe TPC detector. Top right: A layout of the LUX complex in the Davis Cavern of the Homestake Mine at a depth of 4850 feet. LUX is housed in a 6 m diameter water shield. Bottom left: A typical event collected during surface running, showing S1 and S2 signals. Bottom right: The expected reach (black curve) of LUX in the WIMP cross section-mass plane using a full NEST/LUXSim simulation described in the text.

would exclude a large range of cross sections at low masses.

UC Davis is a founding member and one of the larger groups among the 17 LUX institutions. We have contributed strongly to installation, commissioning, maintenance, operations and software tasks. Table 2 shows the various leadership roles and responsibilities assigned to UC Davis personnel over the last two years. Besides our postdocs, grad students and undergrads, our mechanical shop personnel, John Thomson and David Hemer, have traveled to Lead as needed to install the detector support infrastructure, and our electronics engineers, Britt Holbrook and Ray Gerhard, have continued to provide support.

In terms of software, the UC Davis group has contributed strongly in several areas. Szydagis leads NEST[64] software package development and served a 6-month term as Simulations Coordinator starting in December 2012. UC Davis is the primary driver of the ROOT Analysis Group at LUX and Woods serves as its Coordinator. We have also led the effort to reproduce the surface running data in LUXSim[65]. Figure 27 (left) shows the spectrum obtained from a Cs-137 source. The light yield of more than 8 phe/keV (at 662 keV and zero field) is the best achieved in a full-scale dual phase Xe TPC. Uvarov has an algorithm for extracting single phe pulses from the recorded data and using them to determine an in-situ calibration of PMT gains. This is a robust method for tracking

[64] *"NEST: A Comprehensive Model for Scintillation Yield in Liquid Xenon,"* JINST 6 p10002 (2011)
[65] *"LUXSim: A Component-Centric Approach to Low-Background Simulations,"* NIM A 675 63 (2012)

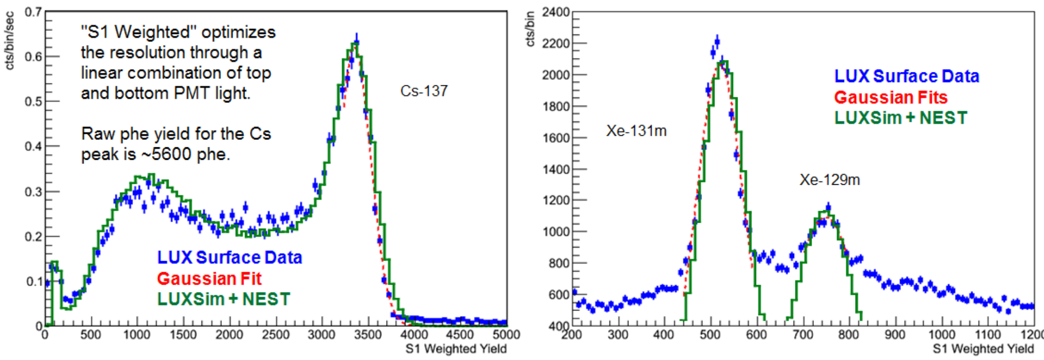

Figure 27: Energy spectra at zero field, plotted in terms of a weighted S1 phe distribution, for a Cs-137 source (left) and in-situ activated Xe-131m and Xe-129m isotopes (right). The full energy deposition peak for Cs-137 at 662 keV is visible, as well as the Compton tail and a back-scatter peak. For activated Xe the lines at 164 keV and 236 keV are mostly contained in the active volume. LUXSim (histogram) describes the data (points) well, yielding a resolution of 5.2% at 662 keV.

Name	Responsibility	Comment
Mani Tripathi	Chair of Executive Committee	Also Electronics, NAA, Spark Getter
Matthew Szydagis	NEST development, LUXSim	Sims Coordinator
Rich Ott	Deputy Science Coord. Manager	Also, LUXSim Detector Geometry
Jeremy Mock	Detector Operations Coordinator	Oversaw underground deployment
Mike Woods	Root Analysis Coordinator	Also Manager, Onsite Computing
Nick Walsh	Water tank PMTs/ Mechanics	writing thesis now
Sergey Uvarov	Muon Veto electronics	Also Xe PMT gain calibration
Brian Lenardo	Piezo microphonics	new student
James Morad	Analog and Trigger Electronics	new student

Table 2: A table of leadership positions and responsibilities of the UC Davis group on LUX.

any drifts. Also, we are now engaged in developing a multi-variate analysis using a neural-network, which is being trained using the unprecedented realism provided by NEST. This will be ready for the analysis of underground data.

5 Task D: Generic Detector R&D

Task D included generic detector R&D work at UC Davis, with Prof. Tripathi taking the leading role. The budget for this task consisted mainly of partial support for a technician, Christian Neher, and some funds to pay for shop recharges. The research work had an emphasis on developing interconnect technologies for semiconductor detectors, using our Facility for Interconnect Technologies (FIT), which was established using ARRA funds, with further studies supported by an ADRD grant. FIT was also engaged in providing bump bonding help to several DOE supported detector R&D efforts, thus providing additional funding from other sources, such as CMS project funds and the Linear Collider R&D funds. The past three years have seen very good progress on several fronts which are reported here. Below is a list of personnel who have been involved in this work.

- **M. Tripathi** (Professor) and **R. Lander** (Professor emeritus) developed small-scale bump-bonding techniques at FIT. They have been involved with the upgrade of CMS tracker and the Si-W calorimeter for the ILC. Their involvement in generic detector development projects has provided a range of detector R&D opportunities for the group.

- **B. Holbrook** (Senior Electronics Engineer) retired during this project period, after serving HEP for 20 years (on D0, CDF, CMS, LUX, Double Chooz and generic ILC R&D). He is now working under a "recall" program at the level of 2 days/week.

- **J. Thomson** (Senior Machinist) managed the departmental machine shop and also retired at the end of this project period. He helped with CMS, LUX and Double Chooz with design, production and deployment. He is now supporting R&D for LZ on a "recall" basis.

- **C. Neher** (Technician) was supported at 33% by Task D, with the rest being derived from other sources. He is an expert on clean-room tasks at the UCD micro-fabrication facility, including mask fabrication, photolithography, wet chemistry, e-beam metallic depositions and scanning electron microscopy. He is also an expert on the operation of various bump bonding machinery in our lab. He presented progress at the TWEPP 2011 meeting in Vienna[66] .

- **M. Woods** (Graduate student) spent considerable amount of time on detector development and has now moved on to LUX detector operations and data analysis. He has gained a lot of expertise in bump bonding and continues to train new students. He has presented talks at the ANT 2011, ALCPG10, and TWEPP 2011 conferences[67] .

Several undergraduate students, A. Moskaleva, R. Fields, and J. Pasner, become experts in operating bonding machines and making measurements. They graduated during this project period and have moved on to grad schools at Berkeley, Rice and Santa Cruz, respectively.

5.1 Developments at FIT

Figure 28 shows some of the machines installed inside a clean room at FIT. They include a Finetech Pico Aligner-Bonder, a West Bond ball and wedge bonder, a dispensing system made by EFD and a Signatone probe station. In addition we have an indium bump deposition system and a fully programmable reflow oven, which complete the suite of instrumentation needed for this work. This is a unique facility in the country. To our knowledge, even the national labs do not have all of

[66] *"Further developments in gold-stud bump bonding,"* JINST 5 C08005 (2010)

[67] *"Development of readout interconnections for the Si-W calorimeter of SiD,"* JINST 6 C12050 (2011)

Figure 28: A photograph of the clean room housing various bump bonding related machines, built using ARRA funds, developed under an ADRD grant, and supported by Task D funds.

this equipment under one roof. As we develop expertise in techniques, we will be able to offer interconnect solutions to a variety of R&D projects.

The facility has been used by several projects, including Si-W calorimeter R&D for the Linear Collider, CMS track trigger R&D and Large Area Picosecond Photosensor Detector (LAPPD) R&D. The techniques that we have developed include indium bump bonding, gold stud bonding, solder reflow bonding and anisotropic conductive film (ACF) attachments. Our old indium deposition system was refurbished with help from the departmental shop. This technology also relies on having a good surface preparation, or under bump metallization. In the past, we have sputtered Ti/W on Al pads with good results. We will continue to develop this technique as an alternative to solder. However, for applications with pad sizes of 50 μm or less, indium is the only known technique.

Lander and Fields worked on attachments using ACF, and have concluded that this process can provide good low resistance bonds, but work needs to be done to get uniformity and consistency in the results. Once developed, this process will offer an extremely inexpensive method for bonding applications that have relatively large pads, of the order of 200 μm or more on a side. We also

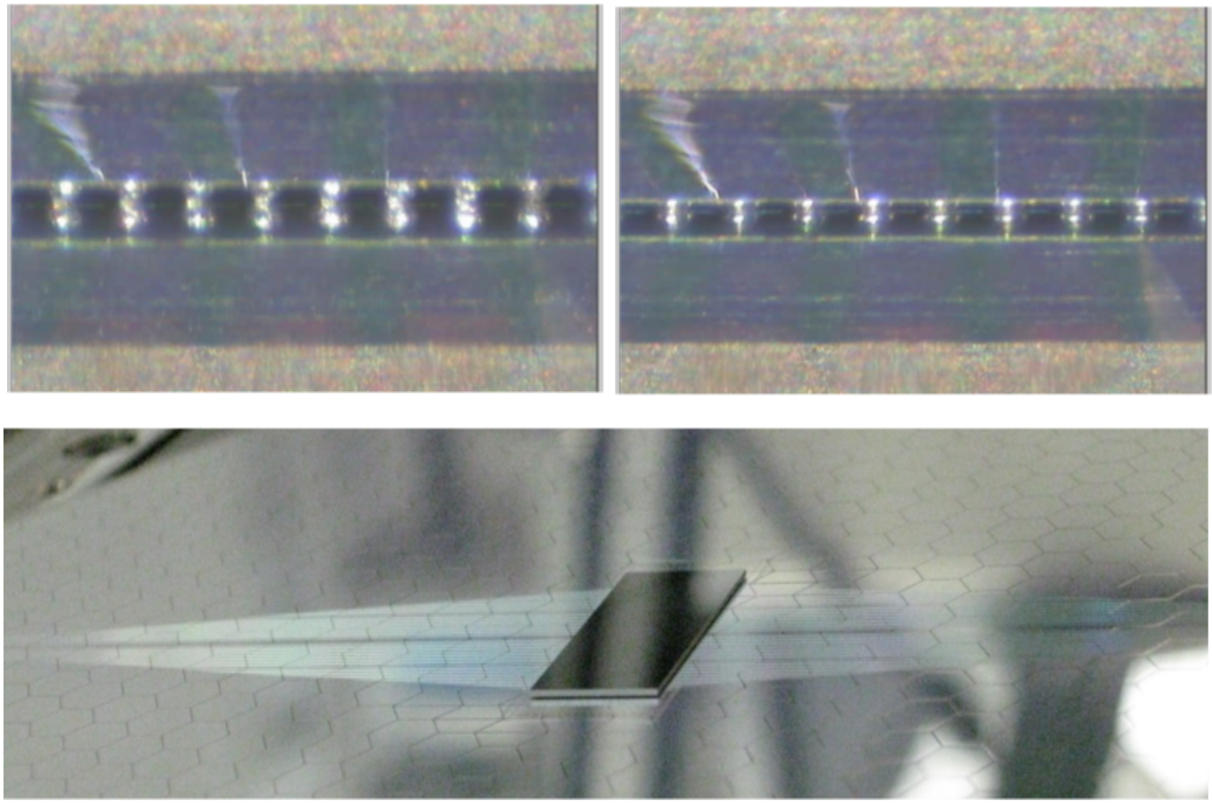

Figure 29: (Top) The reflow process in solder bump-bonding. Individual solder balls and their reflection can be seen on the left (before heating). On the right (after heating) they attach to pads and form bonds. (Bottom) A KPiX chip attached to a sensor wafer after re-flow.

worked on an EFD dispenser that is fully programmable and can deposit about 125 μm or larger drops with good accuracy. The materials that can be used consist of conducting epoxy and solder paste. This promises to be an inexpensive method for forming solder bumps.

Double gold-stud bonding was developed at Davis to address the surface oxide problem on aluminum pads. In the process of stud formation, the gold breaks through the oxide and forms a low resistance contact[68] . In our process, we form gold-studs on the pads of both chips to be bonded. One of the studs is coined, i.e., flattened into a tablet shape. The chips are then attached using a thermo-compression process available on our Finetech aligner-bonder. We have reported this development at the TWEPP 2011 conference and published a paper.

[68] *"Gold-stud bump bonding for HEP applications,"* JINST 5 C08005 (2010)

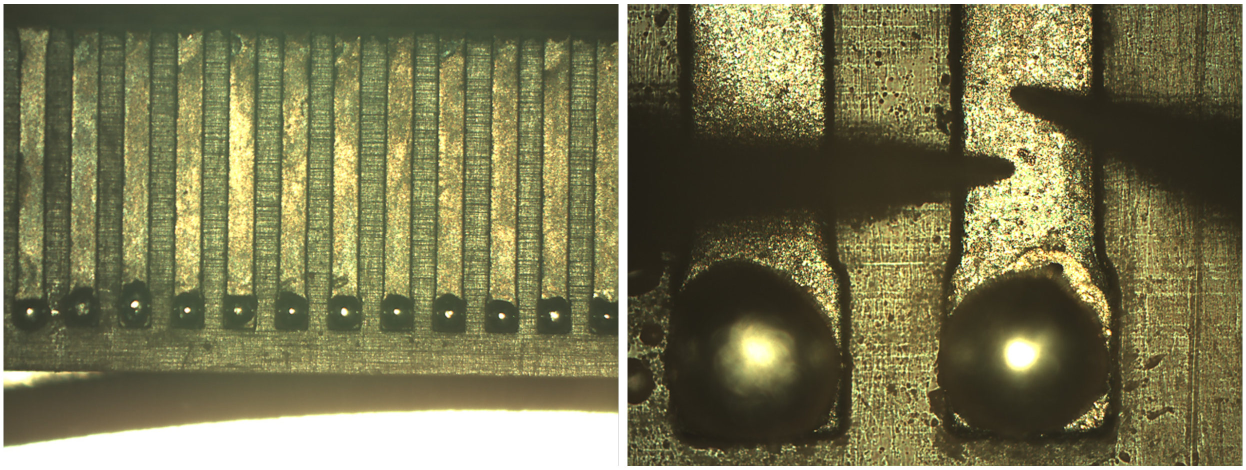

Figure 30: Left: Photographs of solder balls placed on the cable pads and re-flowed. As shown on the right, the balls are well defined and have a diameter of about 200 μm.

For the LAPPD project, we had to work to lower the diameter of the gold studs. That project required very low capacitances at the pads due to stringent speed requirements. We experimented with 0.5 mil gold wire (our usual wire is 1 mil), in order to achieve smaller studs. After considerable effort in tuning the ball-bonder parameters, we bump bonded one PSEC3 chip onto a printed circuit board. It was sent for evaluation to the University of Chicago.

The Si-W calorimeter prototype is being developed in collaboration with SLAC and University of Oregon. UCD has the responsibility for all the interconnect issues, which include bump-bonding, design and fabrication of a cable, bonding the cable to the wafer assemblies, and attaching the corner pads of the wafer using ACF. Figure 29 (top) shows an example of the solder re-reflow process. A KPiX chip is shown being attached to a Hamamatsu sensor wafer. Bumps can be seen to reflow and form connections, with a reduction in their height. This process relies on having a pad surface with nickel and gold layers in order to form good low resistance connections. We worked with a vendor (IZM, Berlin) to provide such a surface using an electro-less plating process or via sputtering of ions. Figure 29 (bottom) shows a KPiX chip attached to the sensor wafer. This work was done by Neher and Woods working with Holbrook.

This assembly was tested with a loop-back 4-point resistance measurement on a set of pads that allowed for this procedure. All bonds showed negligible resistance, much smaller than the inherent trace resistance of about 1Ω. The cables had low-temperature indium solder deposited on their pads, as shown in Figure 30. The solder bumps are well-defined and have a diameter of about 200 μm. The flex cable was attached to the assembly using our bump bonder.

The remaining task of attaching the corner pads (which provide bias and grounds for the guard rings) required a special jig for local heating of the ACF at the corners. Due to differences in the coefficients of thermal expansion between silicon and kapton, care has to be taken to prevent bonds from coming apart after cool-down. As shown in Figure 30 (right), the cable has slots cut into it to prevent such an outcome. This assembly, as shown in Figure 31 (Left), is now at SLAC where

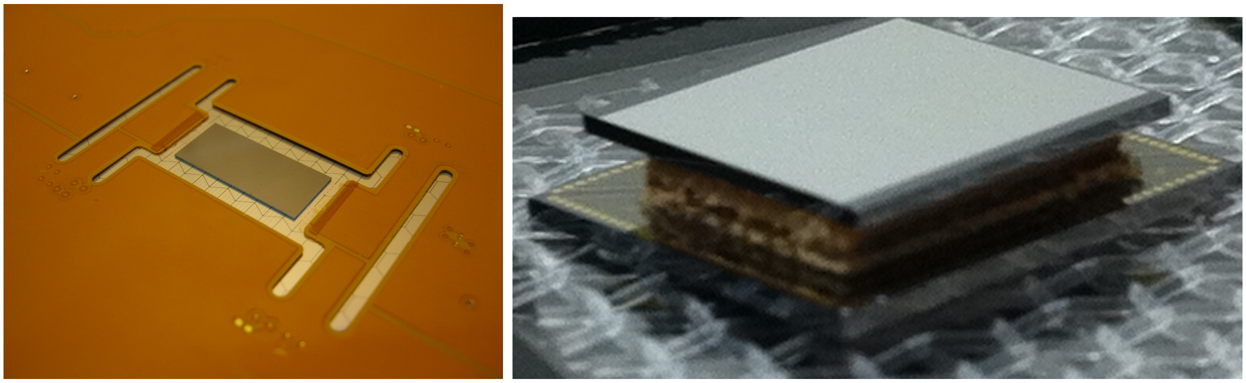

Figure 31: Left: A close up photograph of the KPiX-sensor-cable assembly. Rightt: A photograph of the first prototype triple stack bonded at UC Davis.

it is being tested. The program now consists of fabricating 30 such assemblies to instrument a calorimeter prototype.

The future tracking trigger system must select high P_T tracks at L1 in the extreme luminosity and pileup era of the HL-LHC. We collaborated with FNAL and several universities on a project based on vertically integrated electronics. The basic idea of this proposal is for a series of closely spaced $r - \phi$ planes of silicon strip detectors for which only a limited number of combinations of hits will be consistent with high P_T tracks. The trigger is then based on a fast measurement of tracks by two radially separated planes, with either analog or digital hit information. The 3-D vertical integration calls for a stack of sensors on either side of an interposer and readout chip, a so-called triple stack. During this project period, we received prototype chips and interposers and used our group's bump bonding expertise at UC Davis to bond the first such triple stack, as shown in Figure 31 (Right). This work benefited from the participation of departmental engineers Holbrook and Thompson.