Elementary Particle Physics and High Energy Phenomena:
Final Report for FY2010-13

University of Colorado

DOE Grant Number DE-FG02-04ER41290
Office of High Energy Physics
Program Manager: Alan Stone

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June 27, 2013

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Chapter 1

Experimental Group (Task A)

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1 Overview of the experimental program

The experimentalists under this grant collaborate in CMS at CERN/LHC, T2K at JPARC in Japan, and the RD-42 collaboration at CERN. Papers from the earlier BABAR, MiniBooNE, FOCUS, and KTeV experiments were published in the past three years. We are also engaged in detector R&D and other planning activities for future CMS upgrades, LBNE and NA61/SHINE. The following chapters describe each of these efforts in detail.

1.1 Facilities and Technical Support

The University has supported technician Eric Erdos whose skills cover mechanical and electronics design and fabrication. Our resources include dedicated laboratory spaces equipped with precision measuring and circuit board fabrication facilities, machine shops, and access to a high-bay assembly building (former cyclotron lab).

Substantial University funds have facilitated the creation of a large computing capability developed and managed by Software Scientist Doug Johnson. The Colorado OSG GRID cluster comprises 150 Core i7 nodes, with a 900 TB file system. With its 10-Gbps ethernet link to the Colorado resarch network, the system achieves peak CMS data download rates of about 650 MB per second. A separate cluster optimized for lattice gauge calculations contains 44 Core i7 nodes and 7.5 TB of storage. These facilities have provided for the local analysis needs of the theoretical (lattice) and experimental programs, as well as a large contribution to central event reconstruction and skimming (FOCUS, KTeV), Monte Carlo generation (BABAR), and data analysis and simulation for T2K and CMS.

1.2 Personnel Notes

We note here a few transitions over the last three-year grant period. Kevin Stenson was promoted to Associate Professor with Tenure as of August, 2012, and Eric Zimmerman was promoted to Professor the following academic year. Uriel Nauenberg became Professor Emeritus as of June, 2011. In 2010 Postdoc Martin Tzanov left to join the faculty at LSU, and Stephen Coleman and Robert Johnson joined the group. In 2011 Postdocs Shilei Zang and Mauro Dinardo took new positions at Nanjing University and UC Riverside, respectively. Dinardo has subsequently assumed a faculty position at Milano-Bicocca.

In the last three-year grant period four experimental graduate students received their PhD degrees:

- Robert Nelson (2010) assumed a postdoc position at Caltech on CDMS
- Valeria Frisullo (2010) assumed a scientist position in the private sector
- Martin Nagel (2010) assumed a postdoc at Munich on ATLAS
- Bernadette Heyburn (2011) assumed a scientist position at Agilent Technologies

In 2011, graduate student Edelmaier left the program, followed by Drell in 2012. In 2011, graduate students Troy Mulholland, Andrew Johnson, and Scott Johnson joined the group, followed by Michael Krohn in 2012.

Alysia Marino's effort is funded through a DOE Early Career grant. Cumalat, Stenson, and Wagner won a DOE Advanced Detector Research grant, with Wagner as PI; it ended in June, 2013.

1.3 Education and Outreach

We have made an effort to tie our research program into our educational and outreach mission by offering students, especially women and minorities, opportunities to participate in our research. For example, in the past year, we've had six undergraduates working with us on T2K, CMS, and tracking sensor R&D. Several of these have produced senior theses, and/or completed work earning them authorship on our collaborations' papers. From time to time students come to us through our participation in the NSF-REU program.

Cumalat initiated and runs a public Saturday Afternoon Physics Series for adults and high school students, currently in its eleventh year. Over 1000 people attended these lectures last year. Cumalat, DeWolfe, Ford, Marino, Stenson, and Wagner have contributed to the program. The USCMS meeting hosted at Colorado in 2012 included a public lecture by the CMS spokesman. Cumalat and Ford worked with the CU public information office to facilitate prominent stories in the Denver and Boulder newspapers about the Higgs discovery. Ford appeared in a brief local TV interview, and conducted a question-and-answer session with a local science book club.

2 *BABAR* Experiment at PEP-II

Faculty: William Ford, James Smith, Stephen Wagner; Postdocs: Alessandro Gaz

We joined the *BABAR* collaboration when it was formed in 1993. The primary physics goal was to explore CP violation in the B-meson system; definitive observation of CP violation in B meson decays was published in 2001 [1]; the final result [2] gives the CP-violation parameter sin2β with a precision of about 4%. Other highlights have been the observation of direct CP violation in the decay $B^0 \to K^+\pi^-$ [3], measurements of the CKM angle α from $B^0 \to \rho^+\rho^-$ decays [4], and first observation of CP violation from penguin modes with $\eta' K^0$ [5]. The last of these was done by our group in collaboration with Milan.

Our group has concentrated efforts in physics analysis, simulation, software infrastructure, and collaboration leadership. Wagner was the convener of the Tracking group for several years before moving most of his effort to CMS in 2006. Ford replaced Wagner as the Tracking convener, serving for two years. He had a variety of management positions, notably a member of the Executive Board for three years and a member and Deputy Chair of the Publications Board. Smith was an early coordinator of the *BABAR* Monte Carlo production effort. From 2001-2002, he was Computing Coordinator. He served two terms on the Publications Board, one three-year term on the Executive Board, and was also on many Computing committees. Other physics responsibilities are discussed below.

2.1 Physics Analysis

The principal physics interest of Ford and Smith, most recently working with postdoc Gaz, was in charmless hadronic B decays, channels that are "rare" in the sense that they involve the smallest CKM couplings: V_{ub} in tree diagrams, or V_{ts} combined with loop suppression in penguin diagrams. The richness of these potentially interfering small amplitudes presents opportunities to observe new physics or poorly understood Standard Model parameters. They also present, and help illuminate, complications for the Standard Model measurements.

During the past 12 years, we published approximately 25 papers, most of which were solely the result of our group. We have measured branching fractions, charge asymmetries and time-dependent asymmetries of decays involving η, η', or ω mesons. These are typically more precise than other similar measurements from Belle. During the last three years, we published the final three papers in this effort [6, 7, 8].

2.2 Other Activities

Ford, Smith, and Gaz served as co-conveners of the analysis working group in *BABAR* that deals with charmless quasi-two-body B decays, having served successive terms of about four years each. Smith is the *BABAR* representative and convener for rare decays to the Heavy Flavor Averaging Group. This group is responsible for collating and averaging data on these B decays from various experiments, mostly Belle and *BABAR*, with a few contributions from CDF, DØ, CMS, ATLAS; recently there have been many contributions from LHCb. We also produce a summary of the latest averages in a lengthy paper every two years [9]. Smith is also one of three people responsible for all B physics with the Particle Data Group and co-author of two PDG review articles [10, 11].

Simulation Production

We were the first university group in *BABAR* producing MC for general collaboration use, starting at the beginning of 2000. During the many years of production, Colorado produced more MC than any other University group.

Software Activities

Alessandro Gaz served as particle identification (PID) convener for the past three years, providing support to analysts about the use of PID selectors. Gaz also edited the PID chapter of the "Physics of the B-factories" book.

Doug Johnson served for about a decade as the overall manager of the *BABAR* software release system. This work is now complete and Doug has switched efforts to CMS activities.

3 CMS (Compact Muon Solenoid)

Faculty: John Cumalat, William Ford, James Smith, Kevin Stenson, Stephen Wagner; Post-docs: Mauro Dinardo, Alessandro Gaz, Eduardo Luiggi, Keith Ulmer; Graduate students: Brian Drell, Andrew Johnson, Troy Mulholland

The Compact Muon Solenoid (CMS) [12] is a general purpose detector at the Large Hadron Collider (LHC) of CERN. CMS consists of a muon detection and tracking system, electromagnetic and hadronic calorimeters, and an inner tracking system. The primary goal of the experiment is to determine what is responsible for electroweak symmetry breaking: a Higgs boson, multiple Higgs particles, or something else. No less important is finding an answer to the hierarchy problem for which the main candidate is supersymmetry. Searches for many other phenomena are also being conducted ranging from Z' particles to black holes [13].

In 2010, CMS collected data from pp collisions corresponding to $40\,\mathrm{pb}^{-1}$ which is less than 1% of the luminosity recorded by the Tevatron. However, the center-of-mass energy of 7 TeV, being more than 3.5 times higher than the Tevatron, allowed CMS to exclude large regions of phase space for new physics. These data also provided an opportunity to measure the production of particles ranging from pions to top quarks in a new energy regime. In 2011, CMS collected $5\,\mathrm{fb}^{-1}$ which was enough data to eclipse the Tevatron Higgs exclusion region and rule out a Standard Model Higgs particle between 127 and 600 GeV at 95% CL [14]. On July 4, 2012, the CMS and ATLAS collaborations reported the observation of a new particle consistent with a Higgs boson. This observation represents an historic milestone in the field of particle physics, validating the electroweak symmetry breaking framework constructed nearly 40 years ago. Nevertheless, this is just the beginning of the story. The 5σ observation [15] was obtained using $10\,\mathrm{fb}^{-1}$ of data from 2011-2012. During the remainder of 2012, an additional $15\,\mathrm{fb}^{-1}$ of data was collected, which allowed measurements of spin and parity quantum numbers as well as better mass and branching fraction measurements. The current results indicate the new particle is consistent with a Standard Model Higgs boson. In addition to more precise measurements of the Higgs boson, this large data set is being analyzed in searches for new physics. During 2013-2014, the CMS experiment is being improved while the LHC is upgraded to work at 13 TeV. The data to be collected in 2015 will greatly expand the range of our new physics searches, hopefully providing evidence for what lies beyond the Standard Model.

Since December 1, 2009, work by the Colorado group has appeared in ten published papers [16, 17, 18, 19, 20, 21, 22, 23, 24, 25], one submitted paper [26], and one Physics Analysis Summary [27]. The work by the Colorado group is documented in a variety of internal Analysis Notes (AN) [28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41]. Also during this time, the Colorado CMS group has given 19 conference talks and more than 400 internal talks. The papers and talks are listed in App. 1, Sec. 2.

The Colorado group joined CMS in 2005 and faculty now spend $\sim$100% of their research time on CMS. In addition to tracker and central shifts, the group makes service contributions in the areas of tracker operation, track reconstruction, tau identification and triggering, b-physics, and supersymmetry. The Colorado faculty and post-docs have been members of 27 Analysis Review Committees, serving as chair on 7 of them. The group has hosted three relevant workshops during the last grant period: the RD42 Collaboration Meeting in October, 2010, the USCMS Collaboration Meeting in May, 2012, and the DPF Workshop on Instrumentation in April, 2013. The Colorado group works on various physics topics including strange and beauty production, rare beauty decays, Z' searches, and supersymmetry searches. The group is also studying diamond sensors as a possible replacement for silicon pixels in a future upgrade of CMS.

3.1 Detector activities

Since joining CMS, the Colorado group has been working on the silicon pixel detector. This detector is the closest element to the beamline, consisting of three barrel cylinders plus two forward disks on each side of the interaction region. The pixel detector provides three-hit coverage out to $|\eta| < 2.4$ from a total of 66 million $100 \times 150\,\mu\text{m}^2$ sensors. The effort began with commissioning the forward pixel detector at the Tracker Integration Facility at CERN. Our postdoc at the time, Mauro Dinardo, set up the facility and organized the assembly, testing, and calibration of the forward pixel detectors. He also performed many additional tests of the system including the first source tests with the full readout and measurements of the effect of radiation damage. In early 2009 he repaired some parts of the forward pixel system and installed cold fingers to improve the performance. In late 2009 he worked to understand the origin of a strange problem observed in some of the forward pixel detector modules with signals having rise and fall times much slower than acceptable, causing data to be lost. In 2010 he developed a new beam spot monitoring system using tracks reconstructed from pixel hits (pixel tracks) and began a study of the efficiency, purity, and resolutions of the pixel tracks and vertices made from pixel tracks.

In addition to this past activity, the group is currently involved in calibration and monitoring of the pixel detector. We are also looking to the future with plans to work on the upgraded pixel detector. Furthermore, the group is developing diamond detectors to allow tracking in high radiation environments.

Pixels and Tracker DCS

Postdoc: Alessandro Gaz

Since June 2010, Gaz has been part of the Tracker DCS group. This task involves maintenance and bug fixing for the existing PVSS software that operates the CMS Tracker (strips and pixels). He has helped develop new tools for the monitoring and analysis of the CAEN power supply system and the environmental conditions of the CMS Tracker. As part of the DCS team, Gaz participated in the investigation and analysis of the humidity issues within the pixel volume, which currently preclude operations at the design temperature (coolant temperature of $-20°$C). In 2012, as there was no major development activity in DCS, he served only as a Tracker DCS on-call expert.

In January 2012 Gaz participated in the recalibration of the pixel detector at a temperature of $0°$C (compared to $+7.4°$C during the first three years of operation). Running the detector at the lowest possible temperature is important to mitigate the effects of the increasing radiation damage. The calibration work was successfully completed well ahead of schedule and the analysis of the first 2012 data shows that the performance of the Pixel detector in terms of hit efficiency and resolution is consistent with that of the previous years and with the expectations. Gaz continues to be involved in monitoring the performance as the detector accumulates more radiation damage and continues to serve as an on-call Pixel DAQ expert.

DC-DC Converters for the CMS Pixel Upgrade

Faculty: John Cumalat, Kevin Stenson, Steve Wagner; graduate student Andrew Johnson; undergraduate Rachel Helm

University of Colorado is responsible for testing DC-DC buck converters which were designed by Aachen University for the barrel pixel detectors. They will be used for the FPIX pilot detector and the FPIX upgrade detector to be installed in 2016-2017. A new forward pixel detector with an additional third disk necessitates an increase in the number of readout chips. The use of DC-DC converters [42] will be implemented to reduce losses and to supply the increased amount of power to the front-end electronics. Basically, the converters will be mounted on the FPIX carbon fiber support structure and run at an input voltage of 10 V. They supply output voltages of 2.4 V for the analog part of the readout chip (ROC) and 3.0 V for the digital part of the readout chip. The Aachen ASIC chip has gone through several iterations delaying our testing. The latest chip, AMIS5 ASIC, is expected to be mass produced in late 2013. We have prepared for the arrival of the chips and are constructing a testing box capable of maintaining the temperature at -30 degrees Celsius using Peltier-based cooling.

Diamond pixel sensors

Faculty: John Cumalat, Kevin Stenson, Stephen Wagner; Graduate Students: Frank Jensen, Michael Krohn; Undergraduates: Ben Bentele, Darren Schaeffer, Rachel Helm

For extent of this grant, the Colorado sensor group on CMS has primarily (but not exclusively) investigated chemical-vapor-deposition (CVD) diamond sensors as part of the CMS Phase 2 Upgrade Program. This program aims to find the optimal detector upgrades for the High Luminosity (and high radiation environment) LHC (HL-LHC), which is proposed for the early 2020's. We worked under the aegis of the "Development of Radiation Hard Pixel Detectors for the CMS Tracker Upgrade for the SLHC" proposal, for which Simon Kwan at Fermilab and Jean-Marie Brom at IPHC Strasbourg are contacts (and close collaborators).

Over the past year our group has also worked closely with the CMS Pixel Luminosity Telescope (PLT) project, since this is the first detector proposed to go into CMS with diamond sensors bump-bonded onto CMS pixel Read-Out Chips (ROCs). While we report our progress at most weekly PLT meetings, we have decided to remain in the CMS Tracker project, where we have worked since joining CMS, and not formally switch to the PLT (now BRIL) project.

We participated in the world-wide effort to prove CVD diamond sensors can be viable tracking detectors in experiments where extreme radiation hardness is important, such as those at the HL-LHC. We joined the CERN RD42 collaboration in 2009 when we began working with diamond sensors, and we have presented at every RD42 meeting since. Wagner talked at the Spring and Fall RD42 meetings in 2010, 2011, and 2012 while Ben Bentele, a Professional Research Assistant and former Honors student in the sensor lab, talked at the Spring 2013 RD42 meeting. In October 2010 we hosted the Fall RD42 meeting in Boulder.

The main motivation for pursuing diamond detectors is their intrinsic radiation hardness. Other advantages of diamond are lower atomic number, mechanical toughness, low dielectric constant that reduces the load capacitance for readout electronics, fast signal collection time, and high thermal conductivity. The main problem with diamond compared to silicon has two parts. Diamond is grown in plasma reactors on silicon or diamond substrates. When diamond is grown on silicon substrates, large area sensors can be created but since the silicon and diamond lattice spacing do not match, the diamond is polycrystalline with domain sizes of up to a few hundred microns. When diamond is grown on a diamond substrate, it is possible to create monocrystal diamond. Due to the available substrates, monocrystal diamond sensors are generally limited to about 50 mm^2 while polycrystal diamond sensors 200 times larger are possible. While polycrystal diamond can be made of the correct size, it is inferior in performance to monoscrystal diamond. One critical measure of the diamond performance is the charge collection distance (CCD) which is the efficiency for collecting the charge deposited in the sensor (which should be 36 e^-/μm for a minimum-ionizing particle in diamond) times the thickness of the sensor. The CCD is closely related to the mean-free-path of carriers. The CCD for unirradiated monocrystal diamond is very close to the detector thickness, indicating ∼100% charge collection while the polycrystal diamond CCD is at most half of the thickness (and typically less). Our research has also found other issues related to polycrystalline diamond such as sensitivity to environmental conditions and hysteresis.

As a result of these considerations, we developed a two-pronged approach to diamond research. One effort is to acquire, test, irradiate, and retest diamond sensors (either polyscrystal or monocrystal) from established manufacturers such as Element 6 (E6). After initial testing, these sensors are pixellated and bump-bonded onto standard CMS ROCs by our CMS collaborators at Rutgers and Princeton, and then the testing continues both under a ^{90}Sr source at Colorado and in test beams.

Our group works with Kwan and others to test these diamond sensors (along with radiation-hard planar silicon and 3D silicon sensors) as part of the T992 test beam collaboration at Fermilab. In addition to taking shifts and analyzing data, we are the primary institution for delivering operational diamond sensors for the test beam runs. This collaboration is primarily, but not exclusively, a CMS enterprise.

Our second approach to diamond sensors is to work with R&D producers of CVD diamond (primarily LSPM, formerly LIMHP, at Universite Paris 13) to produce large area monocrystal diamond sensor. In addition to LSPM, with whom we're involved in every step of producing sensors other than actually running the reactors, we have also tested large monocrystal sensors from E6 and EDP (a spin-off of AIST [44]). Since this work is primarily funded by our ADR grant and is not CMS-specific (although they could be used in CMS if this research direction succeeds), it will not be described in detail here. However, where synergies enhanced the CMS program, it will be mentioned. The two programs share lab personnel and test equipment.

The sensor lab at Colorado is equipped with several stations for measuring the properties of CVD sensors. This equipment is used to obtain precision CCD measurements of the diamond sensors and to track the time-evolution of sensors. The time evolution is often quite important as some diamond sensors require pumping (irradiation) before they are fully efficient. We have also observed irradiated sensors to build up polarization and develop significantly reduced CCD as a function of time.

To provide properly tested sensors for test beam runs and to measure the CCD of sensors which have been bump-bonded to CMS ROCs, we acquired a CAPTAN DAQ system [43]. The CAPTAN system was designed at Fermilab for the read-out of pixel tracking detectors and three CAPTANs are the basis of the T992 spectrometer read-out. We have had the system since June 2011 and routinely read-out and calibrate diamond and silicon sensors bump bonded onto CMS ROCs. This has allowed us to diagnose the problems which plagued the sensors in the previous test beam. We test all diamond sensors on the Colorado CAPTAN system before they go into the beam. The pixel sensors tested on the Colorado CAPTAN system are illuminated by Sr and Am sources, and we have recently acquired a second CAPTAN system to set up a portable four-sensor cosmic ray/testbeam telescope at Colorado.

We collaborate with Sally Seidel of University of New Mexico in a LANSCE sensor irradiation program at LANL. We sent shift takers and sensors to the August 2011, December 2011, and December 2012 irradiations. We also helped Rutgers prepare sensor assemblies for the December 2011 irradiation as part of the PLT effort. We have two standard sensors at Colorado, a 500 μm E6 monocrystal and a 750 μm thick E6 polycrystalline, that have been irradiated with $\sim 3.5 \times 10^{14}$ protons/cm^2 of 800 MeV protons in this program, and subsequently tested in the T992 beam and at Colorado.

We have also begun working with Stefan Spanier of University of Tennessee (and the PLT project) to irradiate sensors both in the LANSCE beam and a wide-band (1 eV to 10 MeV) neutron beam at ORNL. One monocrystal sensor, also tested at Colorado before (two subsequent) ORNL irradiations (to 4×10^{14} neutrons/cm^2) shows large polarization build-up under high-rate irradiation at Colorado, enough to further reduce its CCD beyond that expected (and observed) from NIEL radiation damage. Tests at Colorado also showed this polarization could be remediated by the application of red light from LEDs or lasers. Both results were reported at PLT and RD42 meetings and subsequently verified by tests on other irradiated PLT sensors (and other irradiated sensors at Colorado).

One recent and important example of the interplay of the different programs is shown in Figure 1.1. A LSPM "mosaic" monocrystal broke into four normal-sized sensors under cutting and polishing. These sensors, grown in the same reactor at the same time, are as close to identical sensors as possible. One was kept unirradiated, one was irradiated to 3×10^{14} protons/cm^2 in Seidel's program at LANL, and one to 3×10^{14} neutrons/cm^2 in Spanier's program at ORNL, so that we could directly compare the effects of irradiation without having to have the unirradiated sensor "pretested." A technique recently became available to measure Nitrogen-Vacancy (NV) centers up to 50 μm into the sensors at Princeton [45]. Since these NV "traps" are at the right place in the diamond band-gap to be sensitive to the red light illumination mentioned above, they are prime candidates for radiation-induced CCD loss due to polarization.

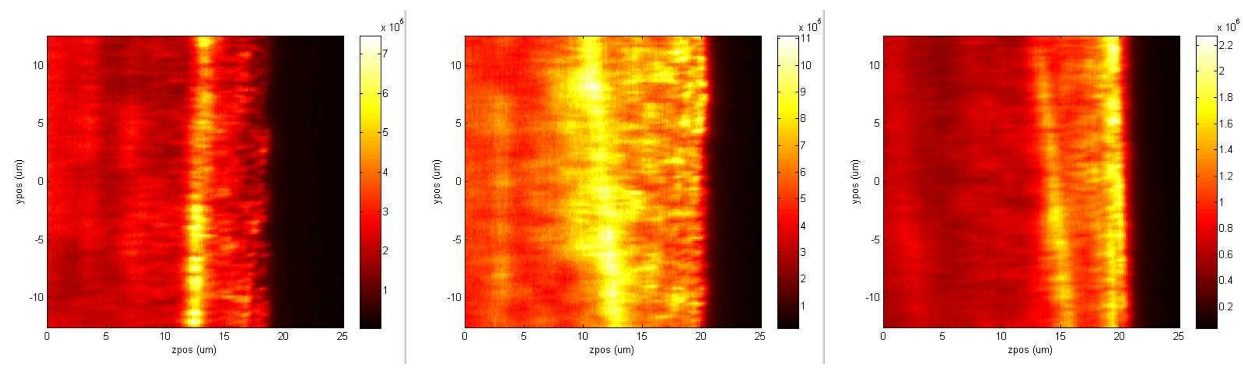

Figure 1.1: Three monocrystal sensors grown simultaneously at LSPM. The sensor on the left has not been radiation damaged, the sensor in the middle has been proton irradiated at LANL, and the sensor on the right has been neutron irradiated at ORNL. The color shows Nitrogen-Vacancy centers in the sensors. The neutron irradiated sensor shows more damage (as NV centers) than the proton irradiated one (the color scale varies between plots and is shown to the right of them - see the text for details).

In Figure 1.1 the diamond sensors show up as red and areas of enhanced NV centers show up as yellow. Note that the intensity scale (shown on the right of each plot) varies from plot to plot. While the proton irradiated sensor (middle plot) shows many more NV centers than the unirradiated sensor (left plot), if they were all to the scale of the neutron irradiated sensor (right plot), the middle plot would appear like the left plot, and the left plot would essentially vanish, except for the yellow band, which would appear dark red. This shows that low energy neutrons are more effective for creating this type (NV center) of radiation damage than protons. A "skin" of damage about 10 μm thick appears to be developing on the neutron-damaged sensor (the zpos, in

μm on the x axis, must be multiplied by n=2.42 of diamond to get the true depth in the sensor). While surface treatments such as polishing or Reactive-Ion-Etching (RIE) may be able to remove this skin, it is hard to see how they will be able to prevent it from building back up once the sensors are back in the real detector such as CMS or ATLAS and accumulating more radiation damage.

The T992 test beam program is just beginning to produce results [46, 47]. The test beam results show that a ROC with a much lower threshold will be necessary if we want to use diamonds sensors at the LHC [46]. This is not only true for diamond but also for 3D silicon and radiation-hard very thin silicon sensors. David Christian is leading the Fermilab part of the CMS effort to develop lower threshold and more radiation-resistant pixel ROC, based on the 65 nm process rather than the current 130 nm one. Colorado has begun working with his group to develop such a ROC. We are currently involved in the measurement of test structures and the planning for irradiations. When real ROCs are produced, we will have them bump-bonded to our diamond sensors and test the complete assemblies through the procedures described above.

3.2 Software development and other service

Tracking POG roles

Faculty: Kevin Stenson

Stenson served as co-convener of the Tracking Physics Object Group (POG) during 2011 and 2012, responsible for track reconstruction in CMS and a level-2 position in CMS. The goals of track reconstruction are quite simple: high efficiency with low fake rate using as little CPU and memory as possible. In addition to providing the tracks for the experiment, the Tracking POG is also responsible for measuring track properties such as efficiency, fake rate, momentum resolution, and impact parameter resolution. Issues related to the primary vertex are a joint responsibility of the Tracking POG and the b-tagging POG although the Tracking POG has generally taken the lead on implementing new algorithms and measuring the efficiency and resolution.

There are approximately 50 ongoing tasks inside the Tracking POG including monitoring the incoming data, measuring the tracking efficiency in data, and adding code to more efficiently find nuclear interactions. To help recruit people, CMS requires authors to work an average of 3 months per year on service projects. The Tracking POG can distribute the equivalent of 150 months of service credit for the 50 identified tasks. Nevertheless, it is a continual struggle to find the manpower to work on these projects, especially since the new physics frontiers opening up are so exciting. Although people have been found to fill the most important roles, the co-conveners are often putting out fires on their own. The Tracking POG conducts biweekly meetings and a weekly joint meeting with the Tracker Detector Performance Group.

Beginning in 2013, Stenson has switched to focusing on track reconstruction with the proposed upgrade detectors, a level 3 position in CMS.

Improving track reconstruction

Faculty: Kevin Stenson

Stenson has been working to improve track reconstruction in CMS since 2006. Track reconstruction in CMS is divided into four *stages*. The first stage is *seeding* which finds two or three initial hits from which to start. The second stage takes the seeds and projects outward to find additional hits. The third stage filters track candidates and performs a final fit. The fourth stage is a cleaning stage which applies quality cuts on the track candidates. These four stages are run multiple times, in different iterations, as part of *iterative tracking*. The first iteration uses seeds constructed from three silicon pixel hits. These seeds must also pass minimum p_T cuts and originate from the production vertex. Subsequent iterations remove the hits associated with already found tracks before trying to find new tracks, reducing the combinatorics and allowing more aggressive track finding. A total of 7 iterations are run, using pixel hits, strip hits, or a combination, with progressively looser requirements on p_T and primary vertex compatibility. Stenson was responsible for the implementation of much of the displaced tracking and performed an optimization of the iterative tracking before the first round of data taking in 2009 and 2010. This optimization was designed to give the best trade-off between efficiency and fake rate.

A new feature of the data collected starting from the summer of 2011 compared to earlier data is the increase in pileup. Pileup refers to multiple proton-proton collisions in one bunch crossing. The pileup has increased from an average of 2 interactions per crossing at the end of 2010 to 10 interactions per crossing in August, 2011, and 25 interactions per crossing by the end of 2012. Although the detector was designed to deal with this, it still presents considerable challenges in a variety of areas, including track and vertex reconstruction. For example, in early 2011 the tracking group realized the current primary vertex finder did not scale well with pileup. Fortunately, we were able to implement another algorithm based on a deterministic annealing method which has been found to scale linearly to at least 24 interactions.

The beginning of 2011 also saw the realization of the role tracking was playing in CPU and memory use during event reconstruction of high pileup events. In particular, memory use was significantly exceeding the required value, resulting in computers with four processing cores only running three simultaneous jobs due to limited memory. As the event reconstruction is the current limiting factor in the CMS trigger rate, this is a critical issue. Several aspects of the track reconstruction were improved to reduce the memory use, allowing the reconstruction code to run on all available resources.

The next identified bottleneck is the actual CPU time taken by event reconstruction. Due to the complexity of tracking, it is not surprising that the track reconstruction accounts for a large fraction (close to 50%) of the event reconstruction time. In addition, it was apparent that the scaling with pileup was highly nonlinear. Therefore, it was essential to reduce the CPU time to avoid severe reductions in trigger rate as the pileup increased. Stenson was able to identify several configuration changes which significantly improved the CPU time with only a small efficiency loss for very low p_T tracks. The effect of these changes was to reduce the average track reconstruction time for a $t\bar{t}$ event with 30 pileup events from 47 seconds to 15 seconds. Furthermore, the efficiency for prompt tracks with $p_T > 0.9$ GeV increased by 1% while the fake rate dropped by 8%. Although these changes were sufficient for the 2011 data, in 2012 the pileup increased by another factor of two, necessitating another campaign to reduce the CPU time. This campaign took place in January and February of 2012. Stenson again retuned the entire iterative tracking, once again reducing the fake rate, CPU time, and memory use with only a small loss of efficiency for very low p_T tracks.

In late 2012, Stenson began work to change the track reconstruction from a single configuration to a variety of possibilities depending on the detector and data. As a result, there is now a configuration for 2012 data, for low pileup data (such as in 2010 or 2011), for the data expected in 2015, and two configurations with the new pixel detector (one for pileup around 70 and one for pileup around 140). He is now working to provide configurations for tracking with a new outer tracker as well. These configurations can be used to extract the best possible performance from the CMS data and are necessary to deal with the variety of possible detector conditions and configurations.

Tracking in dense jets

Faculty: William Ford; Graduate student: Troy Mulholland

Simulations show that for very high jet p_T, the efficiency for finding charged-particle tracks is degraded. This is due to the density of tracks exceeding the granularity of the silicon pixel and strip sensors; the efficiency drops for tracks with angular distance to the nearest neighbor less than about 8 mrad. From samples of QCD jets with p_T around 3 TeV we find a significant fraction of tracks lie within this separation, suffering severe efficiency loss and high fake rate. The density is correlated with track p_T, so that tracks with $p_T > 100$ GeV are reconstructed in the standard tracking code with average efficiencies less than 40%. The effect is evident in some studies of b-tagging, where improvements can be expected to impact the physics.

We have developed algorithms for improving the effective granularity of the sensors. The response of a silicon sensor to a track crossing appears in several adjacent pixels or strips, preprocessed by the pattern recognition code into clusters. The distribution of pulse heights across these elements contains information that can be exploited to determine whether more than one track contribute to a cluster, and if so to split the cluster and recover hits for both tracks. Some time ago we (the Zurich group for the pixels, ours for the strips) established that algorithms that make use of MC truth to split clusters yield substantial gains in efficiency. The ongoing work of the past year seeks to implement a template matching scheme that will free the calculation from its dependence on MC truth.

We have studied the correlation of hit overlap with cluster width and specific energy loss. We've shown that the latter can be adequately determined in a straight-track approximation for the path through the sensor, and that a simple cut on dE/dx can distinguish merged clusters. In the process we identified a significant bug in the strip simulation affecting these merged clusters, which went unnoticed so long as such clusters are rare in most of the phase space of physics interest.

Our collaborators from Johns Hopkins have made considerable progress in developing the template matching scheme, and we continue to work with them and Zurich in studies of the performance. A working version of the code has recently been commissioned into the CMS tracking software packages. The ongoing work will be to streamline the code to the extent possible, and most likely to invent a scheme for deploying it selectively to the most challenging events. Mulholland is working on performance studies, including the primary use case of b-tagging. Ford has made contributions to the B-tagging POG, serving as editor of one PAS [48] and ARC member for another PAS [49].

Other tracking related activities

Faculty: Kevin Stenson; Postdoc: Keith Ulmer; Graduate student: Brian Drell

In 2009 and 2010, Ulmer measured the sensor resolution with a technique using overlapping modules within a tracker layer to minimize the uncertainty from track extrapolation, alignment, and multiple scattering which otherwise would swamp the inherent resolution of the sensors. The values were measured in cosmic and collision data for both the strips and the pixels and compare well with the predicted values used in reconstruction. Ulmer also measured the sensor efficiency for the strip tracker in cosmic and collision data. The sensor efficiency measurement has proved to be a valuable tool in commissioning of the strip tracker. The results from these analyses were published in three papers [16, 17, 18] and presented at many conferences.

Stenson served as editor (with Lenny Spiegel and Morris Swartz) of the tracking and vertex performance paper using data collected in the December 2009 run [18]. Low-level results on the performance of the tracker include signal-to-noise measurements, timing studies, Lorentz angle measurements, calculations of hit efficiency and resolution, and extraction of specific energy loss by charged particles. High-level results highlight the overall performance including comparisons of track parameters with simulation, measurements of vertex resolution, reconstruction of K^0_S, Λ, $\overline{\Lambda}$, $K^*(892)^{\pm}$, $\Xi^{\pm}$, and $\phi(1020)$, measurement of V^0 lifetimes, particle identification of protons, kaons, and pions from dE/dx estimators, reconstruction of photon conversions and nuclear interactions, and an initial test of b-tagging algorithms.

Another tracking paper is currently being finalized [41]. This paper fully describes the track and vertex reconstruction in CMS. It also includes data and MC performance results for a variety of conditions, including the effects of pileup. This includes measurements of track reconstruction efficiency and track resolutions. Stenson is one of the editors of the paper and is in charge of the description of the track reconstruction. The paper should be submitted for publication in the summer of 2013.

τ reconstruction and trigger

Postdoc: Eduardo Luiggi

In CMS, τ decays are reconstructed with a particle flow algorithm, creating a mutually-exclusive collection of single isolated candidates to reconstruct and identify τ leptons. Basically, a τ is defined as an isolated narrow jet. Its identification is accomplished by defining a narrow cone (signal region) around the highest p_T track in the jet where the products of the τ decay are expected to be found. Around the signal cone a larger cone (isolation region) is formed where very little hadronic or electromagnetic activity is allowed.

One problem arises when a photon coming from the decay of a signal π^0 converts into an electron–positron pair and a member of the pair drifts away from the signal into the isolation region under the influence of the magnetic field. If this electron (positron) fails to produce a reconstructable track, it will be identified as a photon candidate by the particle flow algorithm. Since the τ identification algorithm requires no photons above 1 GeV inside the isolation region, the presence of this "photon" would make the candidate fail the isolation requirement, thus rejecting it as a τ candidate. Studies have shown that photon conversions can degrade the τ identification efficiency significantly. The τ identification group decided that one way to recover the lost efficiency was to increase the isolation threshold requirement for photon candidates from 1 GeV to 1.5 GeV. This improves the identification efficiency at the expense of less QCD background rejection. Luiggi developed code to improve the τ identification efficiency by increasing the threshold cut only for photons inside the isolation region that are located within an ellipse with $R_\phi > R_\eta$ while rejecting those candidates with photons outside the ellipse with $E_T > 1GeV$. The effects of using an ellipse is to decrease the QCD background to $\sim$40% with respect to that obtained by increasing the threshold for all photons in the isolation region while keeping a very high τ identification efficiency.

For electrons and muons, the trigger efficiency is measured using tag and probe techniques. Using $Z\to\ell^+\ell^-$ events, one lepton is required to pass stringent identification cuts (tag), while the second lepton is used as the probe to measure the efficiency. This technique is not suitable for τ triggers because the hadronic τ decays are difficult to distinguish from the much larger QCD background. Therefore, the τ trigger efficiency measurement and monitoring is done with respect to "τ-like" objects, i.e., objects passing strong offline tau requirements. Luiggi developed this method and was able to show that real and τ-like objects have a similar behavior, justifying this method of obtaining the trigger efficiency. Luiggi has also been involved in improving the τ trigger and monitoring its effectiveness.

CMS Tier-3 center

Doug Johnson, John Cumalat and James Smith

The CMS computing model contains four tiers of computing. The single Tier-0, located at CERN, farms out data to seven regional Tier-1 sites, each of which is tied to some number of Tier-2 sites. The U.S. Tier-1 site, Fermilab, serves seven Tier-2 sites. The Tier-0, Tier-1, and Tier-2 sites all have specific responsibilities for the experiment including MC generation and data storage. By contrast, Tier-3 sites are a much more fluid designation. The Tier-3 sites are usually used for private MC generation and running of analysis code. The Colorado CMS Tier-3 grid site comprises 151 machines ($\sim$1200 cores) in the experimentalist cluster. The Colorado CMS Tier-3 generally runs $\sim$3000 jobs/day with a high success rate and has processed nearly 6 billion events in the last year.

USCMS Tier-3 support is handled by Rob Snihur at Fermilab (full time) and Johnson at Colorado (half time). As part of the support team, Johnson provides technical assistance to more than 20 USCMS Tier-3 sites. This includes support for the Open Science Grid (OSG) software stack (Compute Element, Storage Element, file systems, etc); installation and configuration of the CMS software; recommendations for security best practices; and helping to organize the yearly USCMS Tier-3 meeting and workshop, the USCMS Tier-3 component of the bi-yearly OSG All Hands meetings and the USCMS Tier-3 bi-weekly EVO meetings. Johnson regularly gives talks at the USCMS Tier-3 and the OSG All Hands meetings. The technical assistance and support often involves Johnson being given root access on remote sites. He then does everything from debugging problems to near complete installations, configurations and maintenance for the site.

In the Spring of 2012, CMS decided to include the CMS Tier-3 sites in its MC production effort. Johnson worked with the CMS MC production team to get Colorado certified as the first USCMS Tier-3 MC production site, and we now make a substantial contribution, as one can see in Fig. 1.2. Johnson now serves as the USCMS Tier-3 liaison to get other USCMS Tier-3 sites integrated into the CMS MC production effort. In addition, the new CMS computing model includes utilizing all CPU cycles at any site willing to donate time. CMS is very interested in utilizing CPU cycles at the Tier 3 sites. This will require updating all the software at Tier 3 sites and making sure these sites can run reliably. Johnson will be working closely with all participating USCMS Tier 3 sites to fulfill this CMS computing model requirement.

University of Colorado has made notable contributions to the Tier-3 center. Beyond supplying HEP computing space, the university provides $60K per year toward Tier-3 equipment and has contributed more than $500K to meet the expanded power, cooling, and network requirements. During the past year the university funded an upgraded 10Gbps network link and invested in manpower to allow it to be fully exploited. Our group has maximized the contributions by building the racks and computers by ourselves.

Finally the Colorado Tier-3 site has been tremendously useful in n-tuple production, not only for our physics analyses, but also helping out others. It is not uncommon to see job failure rates of 20% or even larger when a site is having problems. It is time consuming to run completely on a dataset when the failure rate is that high. Since the failure rate at Colorado is typically below 1%, we can do n-tuple production in typically 2-3 days while it can take more than a week if data is only available at problematic sites.

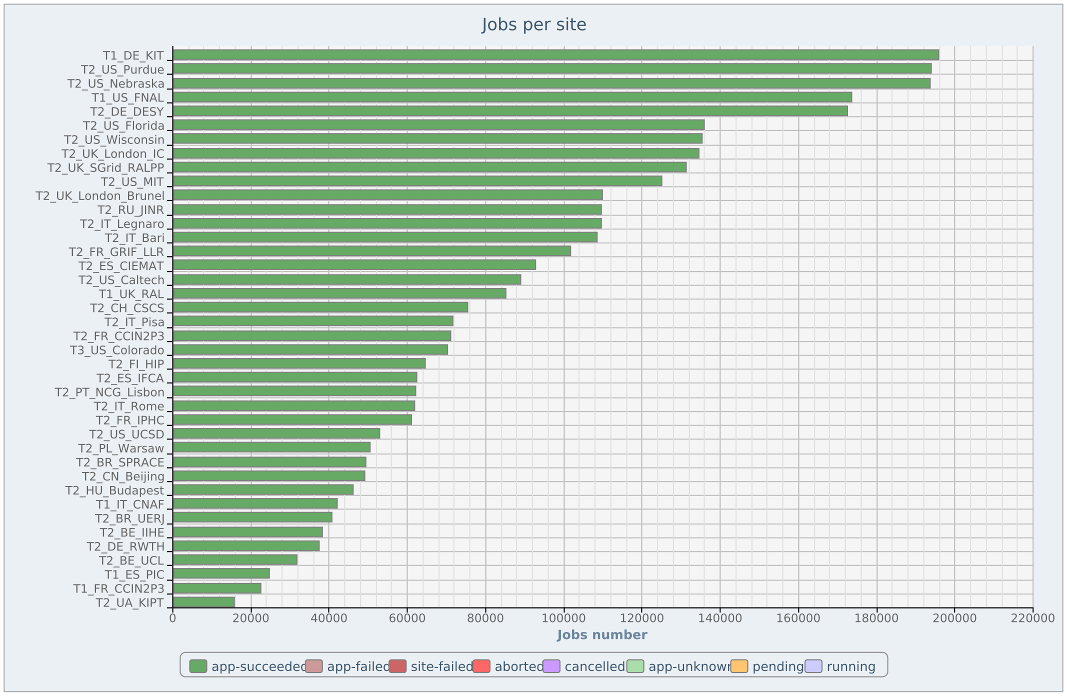

Figure 1.2: The number of CMS MC production jobs successfully completed during August 2012 for the top 40 sites. T3_US_Colorado, half way down the list, is the only Tier-3 site appearing in this graph. Many Tier-2 sites are not shown since they are not in the top 40 production sites. This period does not include the latest 30% upgrade of the cluster in late August 2012.

3.3 Flavor physics

Production of strange hadrons
Faculty: Kevin Stenson; Postdocs: Eduardo Luiggi, Keith Ulmer; Graduate student: Brian Drell

Our group prepared a PAS on the production of strange hadrons for ICHEP in July 2010. Following ICHEP, we made significant improvements to the analysis including adding an additional low-p_T track collection to increase the efficiency and moving to a two-dimensional efficiency correction for K^0_S and Λ to reduce systematic effects. The final published version of the strange-hadron production analysis [19], based on our AN [28], is a significant improvement over the original PAS.

The primary physics results of this analysis are efficiency corrected distributions of K^0_S, Λ, and Ξ^- versus rapidity (y) and transverse momentum (p_T). The results are reported as corrected yields per non-single-diffractive (NSD) event. The selection of candidates generally require the candidates to be well separated from the primary vertex, with a momentum vector that points back to the primary vertex, and for the daughter particle trajectories to miss the primary vertex.

While it is impossible to show all of the results from the paper, Fig. 1.3 gives an idea of the information available. The left panel shows the p_T distributions for the three strange hadrons overlaid with results from recent experiments. The ability to reconstruct low momentum tracks is reflected in the fact that CMS is the only experiment to measure the production down to $p_T = 0$, providing the ability to accurately measure the entire shape of the p_T spectrum. The right panel shows the ratio of three Pythia predictions to data versus p_T. This not only shows that the MC produces fewer strange particles, especially Ξ^-, but also that the p_T distribution shapes are quite different between data and Pythia.

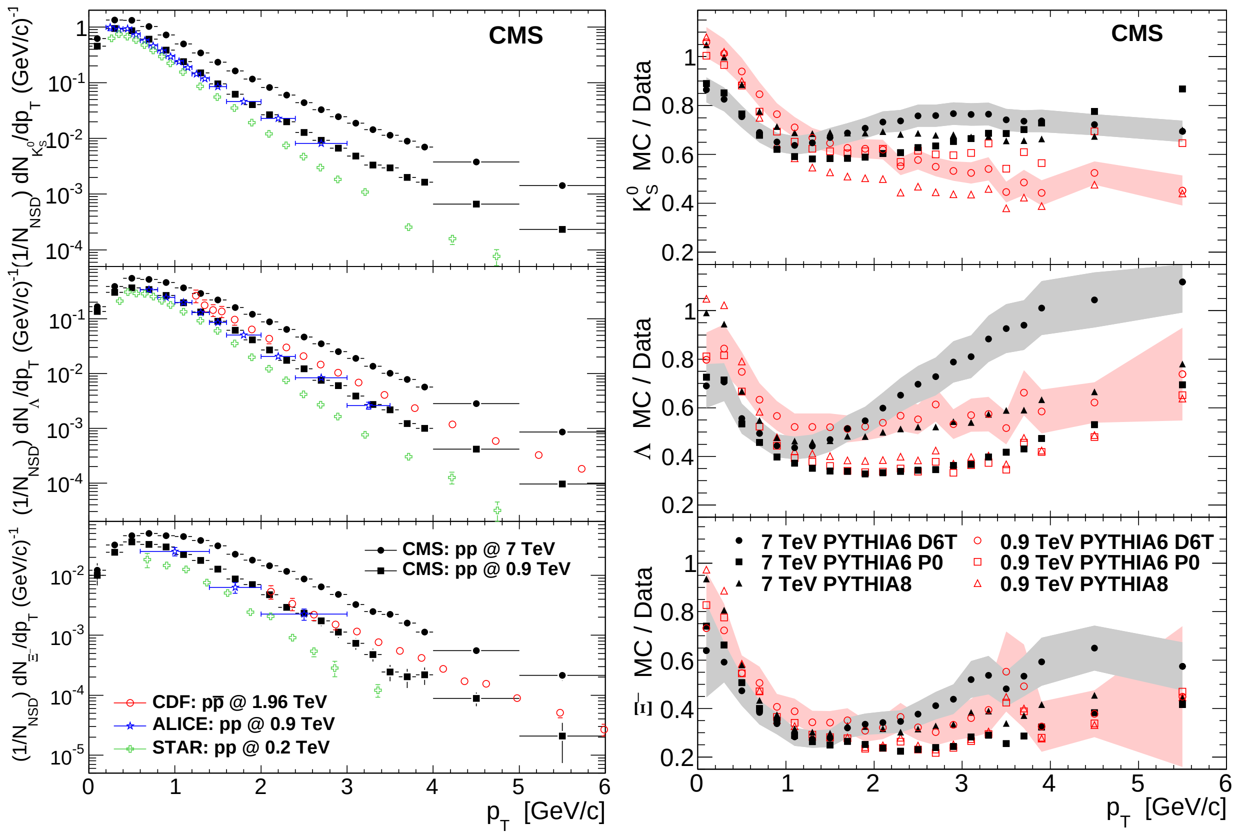

Figure 1.3: The left plot shows the K^0_S (top), Λ (middle), and Ξ^- (bottom) distributions versus p_T with error bars on the CMS, CDF [50], ALICE [51], and STAR [52] results coming from the combined statistical and systematic uncertainties. The right plot shows the ratio of three Pythia predictions to the data results for K^0_S (top), Λ (middle), and Ξ^- (bottom) versus p_T. To reduce clutter, the uncertainty, shown as a band, is included for only one of the predictions (D6T).

In addition to publishing, we have also made this analysis available through Rivet [53]. This allows anyone to generate the plots in the paper using any Monte Carlo generator they wish which should make tuning of MC generators simpler, faster, and more comprehensive.

b physics analyses

Faculty: Kevin Stenson; Postdocs: Mauro Dinardo (now at UC Riverside), Keith Ulmer; Graduate student: Brian Drell

Copious production of heavy flavor particles at the LHC has allowed CMS to publish a variety of interesting results. The initial effort by Colorado was to measure the production of b-hadrons by reconstructing exclusive decays containing a J/ψ and a V^0, building on our experience in V^0 reconstruction. Work continues on production measurements and also on measurements of rare decays.

The first b-physics analysis by the Colorado group was a measurement of the production of B^0

mesons reconstructed in the $J/\psi K_S^0$ decay mode with $J/\psi \to \mu^+\mu^-$ and $K_S^0 \to \pi^+\pi^-$. This analysis was based on the full 2010 data set of $40\,\mathrm{pb}^{-1}$ and was led by Ulmer. The analysis was carried out by performing a two dimensional maximum likelihood fit to the B^0 mass and lifetime with fitting tools based on RooFit developed for this purpose at Colorado. Invariant mass and lifetime distributions for selected B^0 candidates are shown in Figure 1.4, where a clear signal peak is visible. Fits were performed to extract the signal yields in different bins of B^0 p_T and rapidity to determine the differential production rates. This work was published in PRL [20] based on the AN [29]. The differential production cross sections $d\sigma/dp_T$ and $d\sigma/dy$ of the B^0 meson will help to resolve open theoretical questions on heavy flavor production by providing measurements at $\sqrt{s} = 7$ TeV.

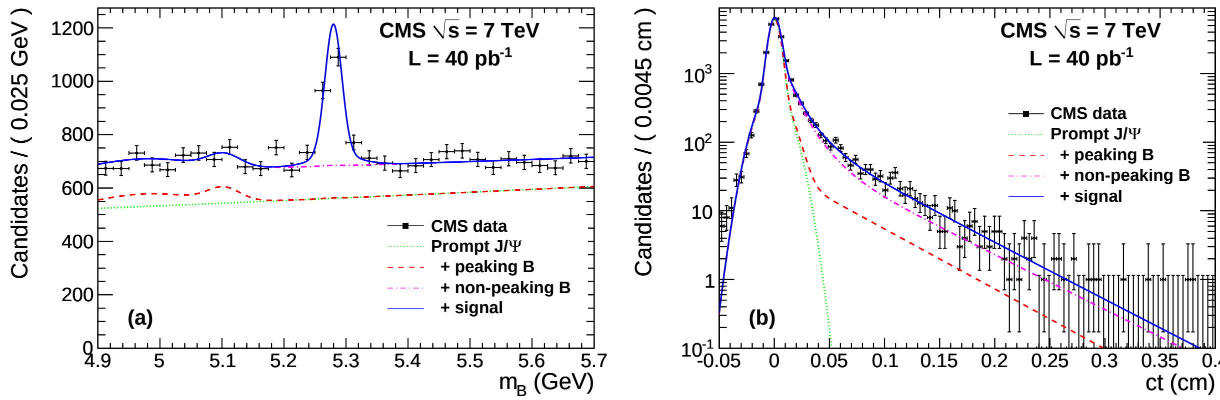

Figure 1.4: $J/\psi K_S^0$ invariant mass (left) and lifetime (right) distributions from $40\,\mathrm{pb}^{-1}$ of data with B^0 signal and various background contributions as labeled.

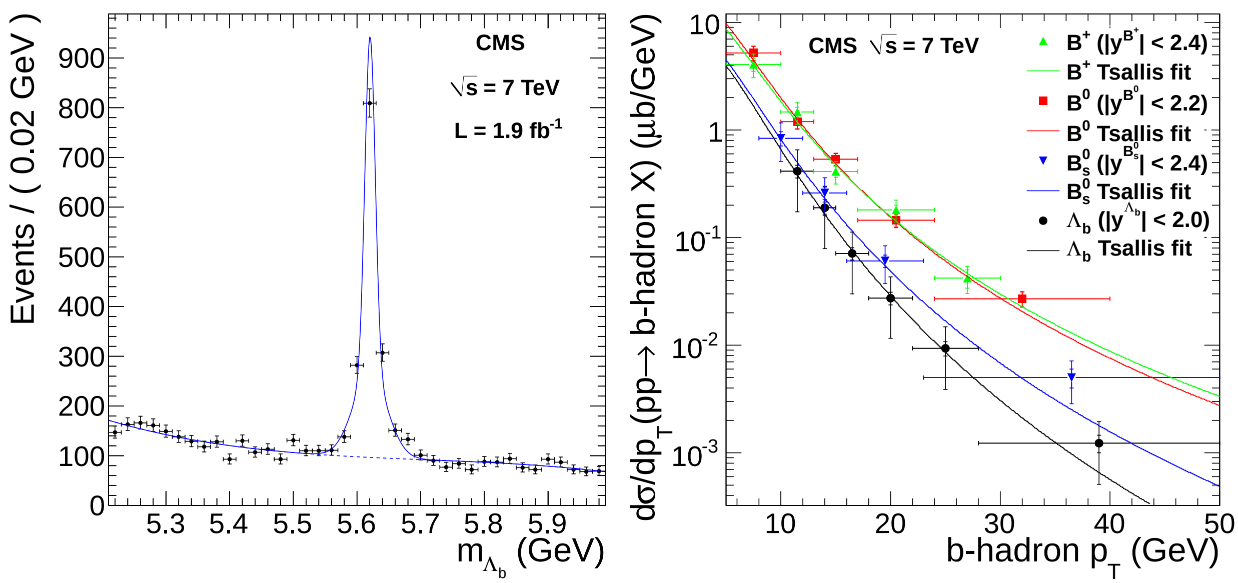

Figure 1.5: The $J/\psi\Lambda$ invariant mass (left) and $d\sigma/dp_T$ for B^+, B^0, B_s^0, and Λ_b (right) with superimposed fits to the Tsallis function described in the text.

Following the success of the B^0 production measurement, Ulmer continued with an analysis of Λ_b production using the topologically identical decay mode: $\Lambda_b \to J/\psi \Lambda$ with $J/\psi \to \mu^+\mu^-$ and $\Lambda \to p\pi^-$, described in an AN [30] and published in PLB [23]. Due to a lack of statistics, this analysis was not possible with the 2010 data. During 2011, the trigger requirements changed frequently so a selection of the early data with relatively loose trigger criteria was used. As the trigger required a displaced dimuon vertex, the prompt background was heavily suppressed and therefore only one-dimensional fits to the invariant mass were needed. In addition to measuring $d\sigma/dp_T$ and $d\sigma/dy$, the ratio $\sigma(\Lambda_b)/\sigma(\overline{\Lambda}_b)$ was measured versus p_T and y and found to be flat and consistent with unity. The integrated mass plot is shown in Fig. 1.5 (left). The fully corrected result for $d\sigma/dp_T$ is shown in Fig. 1.5 (right). Also shown are the results from the B^+ [54], B^0 [20], and B^0_s [55] analyses. All of the results have been fit with a Tsallis function [56]: $\frac{1}{N}\frac{dN}{dp_T} = C\, p_T \left[1 + \frac{\sqrt{p_{\mathrm{T}}^2+m^2}-m}{nT}\right]^{-n}$. Here C is a normalization parameter, T and n are shape parameters, m is the mass of the b-hadron and N is the b-hadron yield. The T parameter represents the inverse slope parameter of an exponential, which dominates at low p_T. Since our data do not constrain that region well, T is fixed to the mean value found from fitting the B^0 and B^+ distributions. The result of $T = 1.10$ GeV is used to obtain the following values of the n parameter, which controls the power-law behavior at high p_T: $n(B^+) = 5.5 \pm 0.3$, $n(B^0) = 5.8 \pm 0.3$, $n(B^0_s) = 6.6 \pm 0.4$, and $n(\Lambda_b) = 7.6 \pm 0.4$. The larger n value for Λ_b indicates a more steeply falling p_T distribution than observed for the mesons, also suggesting that the production of Λ_b baryons, relative to B mesons, varies as a function of p_T, with a larger Λ_b/B ratio at lower transverse momentum.

An analysis to measure the Λ_b polarization and the parity violating asymmetry parameter α_{Λ_b} is ongoing. The full analysis requires fitting five angles that describe the decay. Allowing for both signal and background contributions requires also fitting the invariant mass distribution, increasing the fit to six dimensions. From this fit, seven decay parameters can be extracted, including the asymmetry parameter and the polarization. To maintain full generality, the analysis should be performed separately for the particle and antiparticle. Drell has developed the fitting framework and extracted sensible results from MC signal samples with statistics similar to the data statistics. Measuring the Λ_b polarization is interesting for several reasons. First, it is expected that the Λ_b polarization is approximately equal to the b-quark polarization and therefore this provides information about the production of b quarks. Second, hyperon polarization in hadronic collisions was measured to be much larger than expected from QCD, even at high p_T. It will be interesting to see how this compares with a much more massive baryon. Finally, information on the polarization can be fed back into models of heavy quark production.

While a postdoc at Colorado, Dinardo began the analysis of the rare decay $B^0 \to K^{*0}\mu^+\mu^-$ with $K^{*0} \to K^+\pi^-$. He has continued working with the Colorado group on the analysis while taking a postdoc at UC-Riverside in 2012 followed by a faculty position at Milano-Bicocca in 2013. Reconstruction of this decay is the same as the more plentiful $B^0 \to K^{*0} J/\psi$; the only difference is that the $\mu^+\mu^-$ are non-resonant rather than from a J/ψ decay. This decay is an example of a flavor changing neutral current which is forbidden at tree level in the Standard Model and must proceed via loop diagrams. Contributions from other particles such as from supersymmetry may modify rates and decay characteristics which can be used to discover and identify physics beyond the Standard Model. It has been known for many years that clean, experimentally accessible observables such as the zero crossing of the dimuon forward-backward asymmetry can be predicted robustly in the SM [57, 58, 59], while extensions can dramatically modify this feature [60, 61, 62, 63, 64, 65]. After determining the best selection criteria and obtaining the efficiencies from Monte Carlo, the data were fit to three variables: B^0 invariant mass, $\cos\theta_K$, and $\cos\theta_\ell$ where θ_K and θ_ℓ are associated with the kaon angle and muon angle in the K^{*0} and dimuon rest frame, respectively. The results of the fit give the dimuon forward-backward asymmetry (A_{FB}), K^* longitudinal polarization fraction (F_L), and the branching fraction, all as a function of q^2 (squared invariant mass of the two muons). These results have been released [27] and a paper is in progress. As seen in Fig. 1.6, the measurements of A_{FB} and F_L are more precise than all other experiments but LHCb. As the results can be averaged, the CMS results provide important information constraining new physics. The CMS and LHCb results are both obtained from the 2011 data. In 2012, CMS integrated four times more luminosity while LHCb integrated twice as much luminosity. As the triggers remained approximately the same, CMS should remain quite competitive with LHCb.

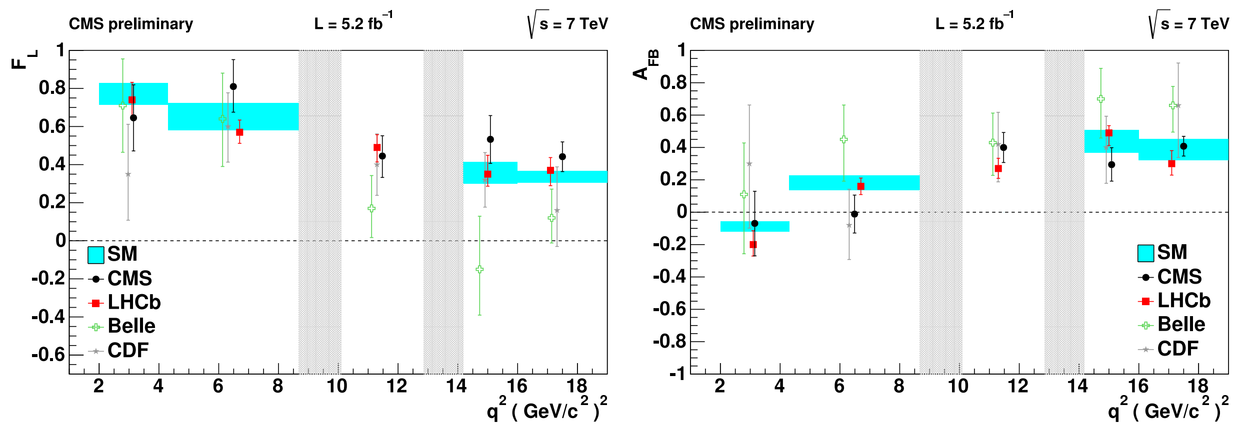

Figure 1.6: Measurements versus q^2 of F_L (left) and A_{FB} (right) for $B \to K^* \ell^+ \ell^-$ from CMS, Belle [67], CDF [68], and LHCb [69]. The error bars give the total uncertainty. The gray shaded regions correspond to the J/ψ and ψ' resonances. The other shaded regions are the result of rate-averaging the Standard Model prediction across the q^2 bins to allow direct comparison to the data points.

Stenson, Ulmer and Drell have all held important service positions in the CMS b-physics group. Stenson has taken on an active roll in the area of trigger development where he has coordinated the design of trigger menus to be used with the evolving LHC luminosity and serves as a trigger contact and Tracking POG contact with the b-physics group. Ulmer was an inaugural co-convener of the exclusive B working group until the end of 2012, making it his job to shepherd the various analyses to completion. During his tenure, he oversaw seven publications including the first observation by CMS of a new particle, the Ξ_B^* [74]. Ulmer was a member of the b-physics editorial board in 2012 and Stenson took over that role in 2013. Members of the editorial board serve as language editors for the papers and also conduct the final reading of the paper after the collaboration review. Ulmer also wrote and maintains the b-physics group's prototype analysis code, which is used as an example for other analyses. Drell served for nearly two years as the b-physics group's MC coordinator. His role included organizing MC production requests for the group and testing new sample configuration files, while providing general assistance with MC related questions. He was also active in producing private MC samples for our group's use with local computing resources.

3.4 Searches for new physics with decays to $\tau^+\tau^-$

Searches for $Z'\to\tau^+\tau^-$

Faculty: John Cumalat; Postdoc: Eduardo Luiggi; Graduate student: Andrew Johnson

Heavy neutral gauge bosons are predicted in several different models - superstring [76], intersecting branes [77], grand unified [78], dynamical symmetry breaking [79], etc. The experimental limits are dominated by ATLAS and CMS. As the mass limits have increased, models in which the Z' couples preferentially to third generation fermions have been proposed [80]. Using 2010 data CMS excluded $\tau^+\tau^-$ resonances at the 95% confidence level with Standard Model couplings for a Z' mass less than 468 GeV/c^2. This result was made public, but was not published.

The Z boson is used as a control peak with a known cross section, mass, and width, then one searches for a high mass excess of events. For Monte Carlo studies, we generated a Z_{SSM} within the Sequential Standard Model (SSM), with scaled masses and widths from the Z. As some models propose non-standard couplings, it is important to search in several Z' states, not just the highly efficient $\mu^+\mu^-$ and e^+e^- states.

At Colorado we are involved in the high p_T $Z' \to \tau^+\tau^-$ working group with Eduardo Luiggi serving as the liaison to the broader Exotica Group. The τ's are identified by being isolated from other tracks. Typically, a single isolated track identifies a τ jet, with the track being a hadron (h), an electron (e), or a muon (μ). At Colorado we have mainly analyzed $Z' \to e^\pm\mu^\mp$, although the basic framework for $Z' \to e^\pm h^\mp$ analysis was developed by Luiggi.

The $e^\pm h^\mp$ and $\mu^\pm h^\mp$ channels have 20% branching fractions, the $e^\pm\mu^\mp$ channel 6% branching fraction, and the $h^\pm h^\mp$ channel a 46% branching fraction. Combining the results from all channels in 2011 data (4.94 fb^{-1}), we improved upon the best $Z' \to \tau^+\tau^-$ limit to exclude $\tau^+\tau^-$ resonances at the 95% confidence level with Standard Model couplings for a Z' mass less than 1.4 TeV/c^2, a 3-fold increase over 2010. The analysis was published in Physics Letters B [24].

In Fig. 1.7 we present a histogram of the $e^\pm\mu^\mp$MET invariant mass (left) with a sample signal of a 750 GeV/c^2 Z$'$ displayed with various background estimates. The plot on the right presents a combined limit from the four independent samples of $\tau^+\tau^-$ decays. The intersection between the combined 95% confidence level and the theory predictions provide the theory dependent mass limit.

Graduate student Andrew Johnson has passed his comprehensive exams and he is analyzing the $\tau^+\tau^-$ events from the 2012 datataking. Our goal is to determine the Z' limits from the 8 TeV data.

A natural extension of the search for heavy resonances decaying into tau pairs is the search for a heavy neutrino and a right-handed W boson. Right-handed W bosons, $W_{\mathrm{R}}^{\pm}$, appear in Left-Right Symmetric Extensions (LRSM) of the Standard Model [81, 82, 83] and are proposed to explain the origin of parity violation in the weak interactions. The right-handed symmetry group, SU_{R} also introduces heavy right-handed neutrinos states N_ℓ ($\ell = e, \mu, \tau$) that partner with the light neutrinos ν_ℓ to explain the origin of the neutrino masses via the see-saw mechanism.

The main production mechanism for a right-handed W boson at the LHC is shown in Fig. 1.8. The methodology and tools developed for the $Z'\to\tau^+\tau^-$ analysis are directly applicable to this analysis.

Search for EWKinos and Sleptons Produced via VBF

Faculty: John Cumalat; Postdoc: Eduardo Luiggi

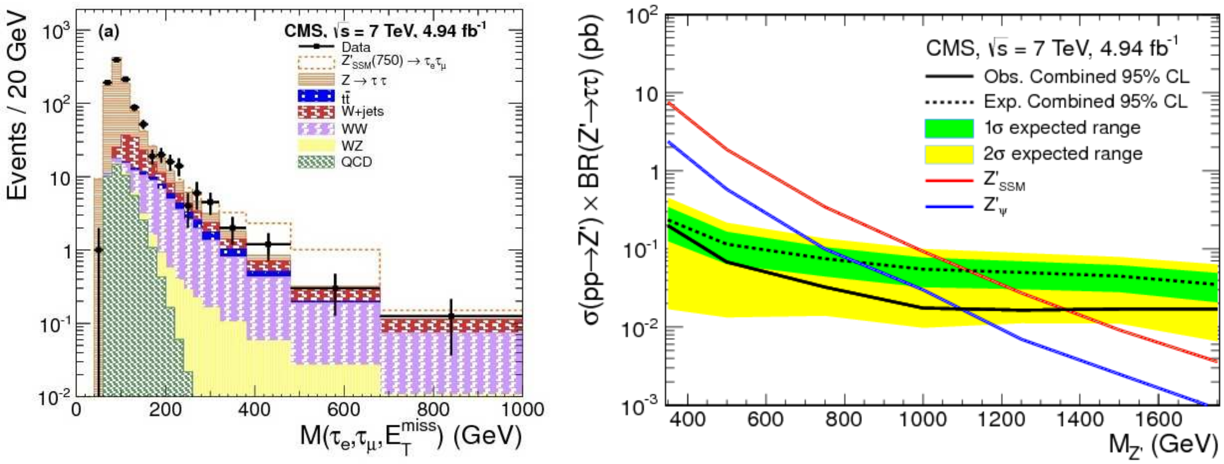

Figure 1.7: The $e^{\pm}\mu^{\mp}$MET invariant mass distribution (left) is displayed for a search for a $Z' \rightarrow \tau^+\tau^-$ resonance. On the right is presented the combined limits from the four independent Z' decay samples. Limits for two different models are presented. The limits determined in this study are four times higher than the world's best previous limit.

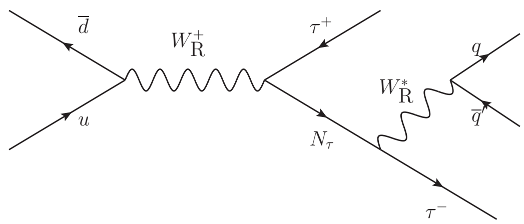

Figure 1.8: Feynman diagram for the production of a right-handed W boson and heavy neutrino decaying to two tau leptons and two jets.

The classic search for charginos, neutralinos, and light third generation SUSY particles is through cascade decays of colored particles such as gluinos and squarks. Colored particles with masses up to 1.5 TeV have been ruled out in a number of channels by both CMS and ATLAS motivating new search strategies that can probe the EWKino sector directly. Vector boson fusion (VBF) processes provide a unique opportunity to search for new physics with electroweak couplings as most backgrounds are heavily suppressed. VBF processes are characterized by two tagging jets with large dijet invariant mass in the forward region in opposite hemispheres. The Feynman diagram for the production of chargino-chargino and chargino-neutralino via VBF is shown in Fig. 1.9.

Luiggi, along with collaborators from Fermilab, Panjab Universtiy, Texas A&M, and Vanderbilt, has searched for light charginos and neutralinos decaying into tau pairs with opposite and same sign charge associated with VBF tagged jets. The VBF requirements are two jets in the forward region with $\Delta\eta(j_1, j_2) > 4.2$ and dijet mass $M(j_1, j_2) > 700$ GeV. The two jets must be in opposite hemispheres with jet p_T greater than 75 and 50 GeV for the leading and sub-leading jet, respectively. In addition, the event is required to have missing transverse energy greater than 75 GeV in order to account for the LSP and the neutrinos from the tau decays.

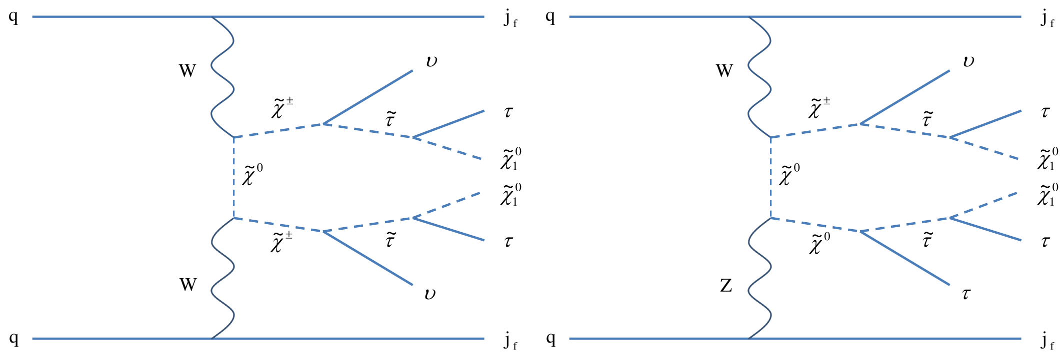

Figure 1.9: Feynman diagram for the production of chargino-chargino (left) and chargino-neutralino (right) via VBF

The analysis uses a data-driven background estimation for the largest backgrounds, *e.g.*, $t\bar{t}$ and the production of W bosons in association with one or more jets (WJets). Control regions dominated by the main backgrounds are chosen to measure the efficiency of the VBF selection requirement directly from data. In Fig. 1.10 we show the Dijet (j_1, j_2) mass and $\Delta\eta$ distributions for events in the $t\bar{t}$ control region.

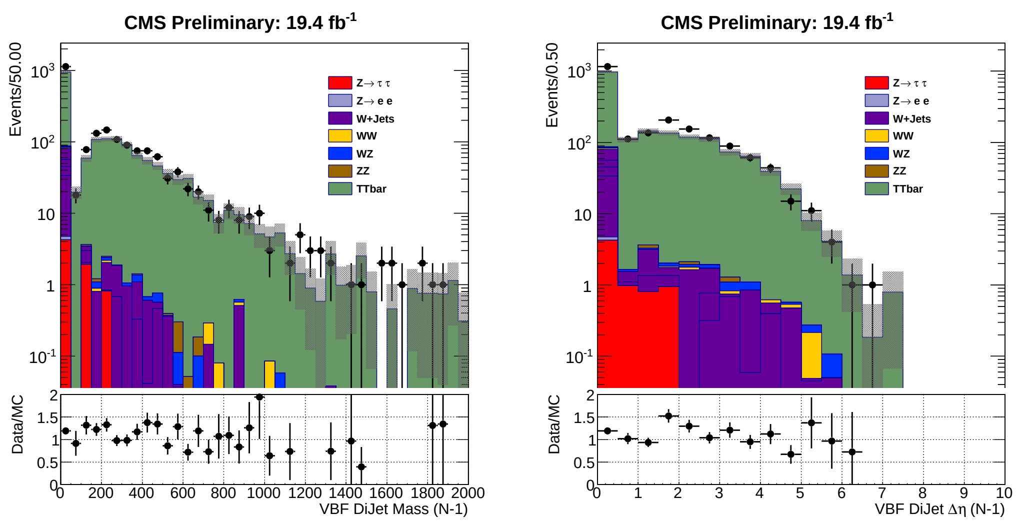

Figure 1.10: DiJet mass and $\Delta\eta$ distributions for events in the $t\bar{t}$ control region.

This analysis is ongoing and is expected to be completed in early 2014. An updated version of the analysis using VBF dedicated triggers will provide enhanced sensitivity to the search.

Dark Matter Phenomenology

Postdoc: Eduardo Luiggi

Luiggi and collaborators performed a feasibility study of the prospects for detecting supersymmetric dark matter (DM) produced directly at the LHC via the VBF production mechanism at a center of mass energy of 14 TeV. In the case when the chargino ($\chi_1^{\pm}$) and neutralino (χ_0^0) masses are highly degenerate, the main signature of the decay would be large missing transverse energy and nothing else. This decay can be triggered and studied with the presence of two tagging VBF jets. It was also shown [84] that information about the production cross-section and the missing transverse energy distribution provides insight on the composition of the LSP and hence the DM relic density.

3.5 Searches for Supersymmetry

Ford and Smith, working with postdocs and students, have been involved in a program of searches for Supersymmetry since joining CMS. We describe in the following two subsections an initial search for multilepton signatures with the 2010 data sample and our more recent analysis of hadronic final states with b-tagged jets.

Multilepton signatures for new physics

Faculty: William Ford, James Smith; Graduate student: Christopher Edelmaier

Among final states reconstructed in CMS that are least populated by Standard-Model processes are those with multiple leptons. In some scenarios new physics will produce such states. An example motivated by CMSSM [85] is the direct production in the pp collision of a chargino $\tilde{\chi}_1^+$ with a neutralino $\tilde{\chi}_2^0$. The lightest SUSY state, $\tilde{\chi}_1^0$, is stable and non-interacting. The decays are $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \ell^+ \nu_\ell$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$. The signature is therefore three charged leptons and missing energy. Searches for this process were first published by CDF [86] and DØ [87]. An alternative production mechanism is via squarks, yielding a decay chain with three or more leptons and jets. This is expected to dominate for pp collisions of 7 TeV or higher. The Colorado group, along with groups from UC Davis, Karlsruhe, and Rutgers, has produced first physics results for these channels.

The basic requirements are three or more isolated leptons with $p_T > 8$ GeV/c, pseudorapidity $|\eta| < 2.4$. The background can be reduced further by requiring the total jet energy to be at least 200 GeV. We observe no significant signal in the 35 pb^{-1} 2010 data sample.

Accounting for observed yields and expected background contributions with systematic uncertainties included, we obtain 95% exclusion limits as shown in Fig. 1.11. With this small dataset, we already excluded a region slightly larger than the previous Tevatron experiments. This result was published in 2011 [21].

Search for supersymmetry in hadronic final states with b-jets

Faculty: William Ford, James Smith; Postdocs: Alessandro Gaz, Keith Ulmer; Graduate student: Troy Mulholland

Many new physics models are predicted to contain final states that are rich in bottom-jet production. In particular, supersymmetric scenarios with large values of $\tan\beta$ generally result in enhanced couplings to b, t, $\tilde{b}$ and $\tilde{t}$, all of which produce bottom jets in our detector. Models with LHC SUSY production cross sections dominated by gaugino and gluino pair production often result in final states with a distinct 4 b-jet signature. SUSY signatures with b-jets have recently garnered additional attention with the observation of a Higgs boson. Quadratically divergent contributions to the Higgs mass could be canceled by new partner particles. The most significant term arises from the top quark for which a light $\tilde{t}$ could provide an appropriate cancellation, suggesting that

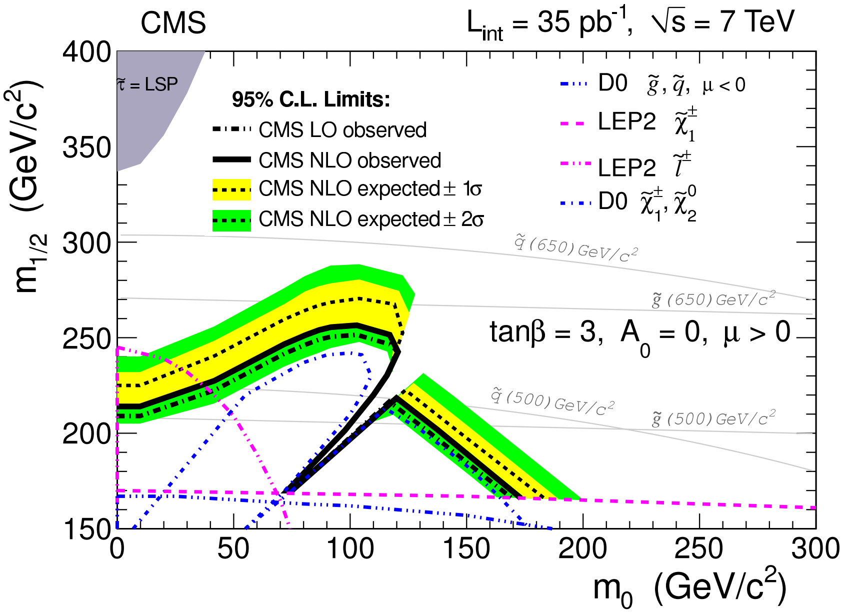

Figure 1.11: Limits at 95% CL for a CMSSM scenario along with Tevatron and LEP limits.

searches with b-jets will likely hold the answer to whether natural SUSY is the solution to the hierarchy problem.

The Colorado group, along with collaborators from UC Riverside, UC Santa Barbara and Cornell, has produced a result on such searches for new physics with b-jets as described in a detailed analysis note [36] and a paper published last year in Physical Review **D** [25]. These results are based on the 7-TeV 2011 dataset and are an update, after a substantial reoptimization, of a preliminary result released in October 2011 [88].

The characteristic signature for these searches contains large missing energy carried away by the undetected LSP's (lightest SUSY particle) and large hadronic jet activity due to the cascade decays of the squarks, along with identifying at least one of the jets as arising from a bottom quark. Our 7-TeV search required a minimum of 150 GeV of missing transverse energy ($\not{E}_T$) and at least three jets with a minimum scalar sum of 400 GeV of transverse jet momentum (H_{T}). Different tighter search regions were defined with more restrictive $\not{E}_T$ and/or H_{T} requirements in addition to requiring ≥ 1, ≥ 2 or ≥ 3 identified b-jets.

The dominant background arises from $t\bar{t}$ events with two real b-jets. QCD multi-jet backgrounds are suppressed by requiring a minimum separation in angle between the $\not{E}_T$ and each jet, while electroweak backgrounds are suppressed by rejecting events that contain an isolated muon or electron. The b-jet requirement is also quite effective in rejecting all backgrounds with minimal b content. An irreducible contribution arises from $Z \to \nu\bar{\nu}$ decays, where the neutrinos create true $\not{E}_T$. We show in Fig. 1.12 typical $\not{E}_T$ distributions for the various backgrounds, typical b-rich signals (T1bbbb and T1tttt) and the data from the 2011 analysis.

The analysis is characterized by a strong reliance on data-driven background estimates, which have been made for each of the main sources of background. This technique avoids depending on MC simulation as much as possible. The Colorado group has developed the method to measure the background from $Z \to \nu\bar{\nu}$ by reconstructing events with $Z \to \mu^+\mu^-$ or $Z \to e^+e^-$ decays and simulating

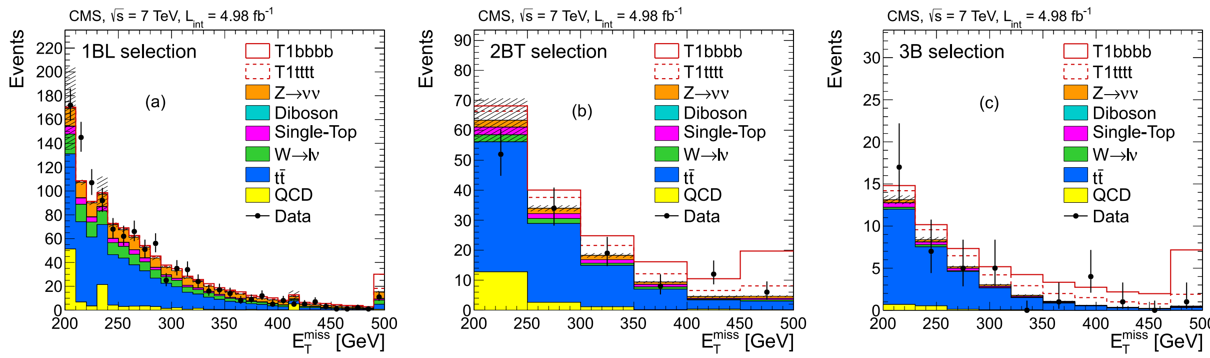

Figure 1.12: Distribution of $\not\!\!E_T$ for the ≥ 1 b-jet loose, ≥ 2 b-jet tight and ≥ 3 b-jet selections from left to right in comparison to the SM background predictions. The hatched bands show the combined statistical and systematic uncertainties on the total standard model prediction from data-driven techniques. Typical b-rich signals from the T1bbbb and T1tttt models are shown in red.

the $\not\!\!E_T$ by treating the reconstructed charged leptons as if they had been neutrinos.

We study the T1bbbb and T1tttt simplified models[89], involving pair production of gluinos each of which decays to two b quarks or two t quarks and an LSP through a virtual sbottom or stop as shown in Fig. 1.13. This probes a region of phase space with light gluinos and third generation squarks that remains viable as a SUSY solution to the hierarchy problem. No significant excess of data events was observed above SM backgrounds, and we show in Fig. 1.13 the 95% CL cross section upper limits and exclusion regions for these models.

For the 7-TeV publication, our group was responsible for the optimization of the signal selection requirements, and the measurement of the $Z \rightarrow \nu\bar{\nu}$ background, and contributed to the technical development of the procedure to obtain the upper limits from the fit. The signal selection optimization proved particularly valuable where we obtained an improvement of a factor of ~ 3 for the final result over the preliminary result, which represents a factor of ~ 1.5 better than simple scaling by $\sqrt{\mathcal{L}}$ due mostly to the reoptimization. We were also extensively involved in n-tuple production, development of the maximum-likelihood fitting code and studies to improve the analysis with more complex fitting in multiple dimensions.

We developed an improved version of the analysis for the 2012 8-TeV data sample. The Colorado group has led the effort for the most significant improvement, which is the application of a multidimensional fitting procedure. The more sophisticated fitting technique, taking advantage of different shapes in three dimensions (number of b-jets, H_{T}, and $\not\!\!E_T$) between signal and background, improves the results in the search for T1bbbb by a factor of $2-4$ over a cut and count approach. We produced a preliminary result with the 8-TeV 2012 data sample for the Moriond 2013 conference. The final version of the analysis is described in an internal note [37] and was recently submitted for publication [26]. The 95% CL upper limit contours corresponding to those shown in Fig. 1.13 are given in Fig. 1.14. The excluded masses are 200-300 GeV higher than those for the 7-TeV analysis.

Colorado members contribute to the SUSY Physics Analysis Group (PAG) in several ways. Ulmer is a convener for a SUSY working group, responsible for gluino-mediated decays. Ford serves on the SUSY editorial board, whose members are designated to help the analysis groups prepare their manuscripts for publication. Members of this board also serve on the CMS publication committee that oversees the quality assurance for the collaboration's public results. Ford is the

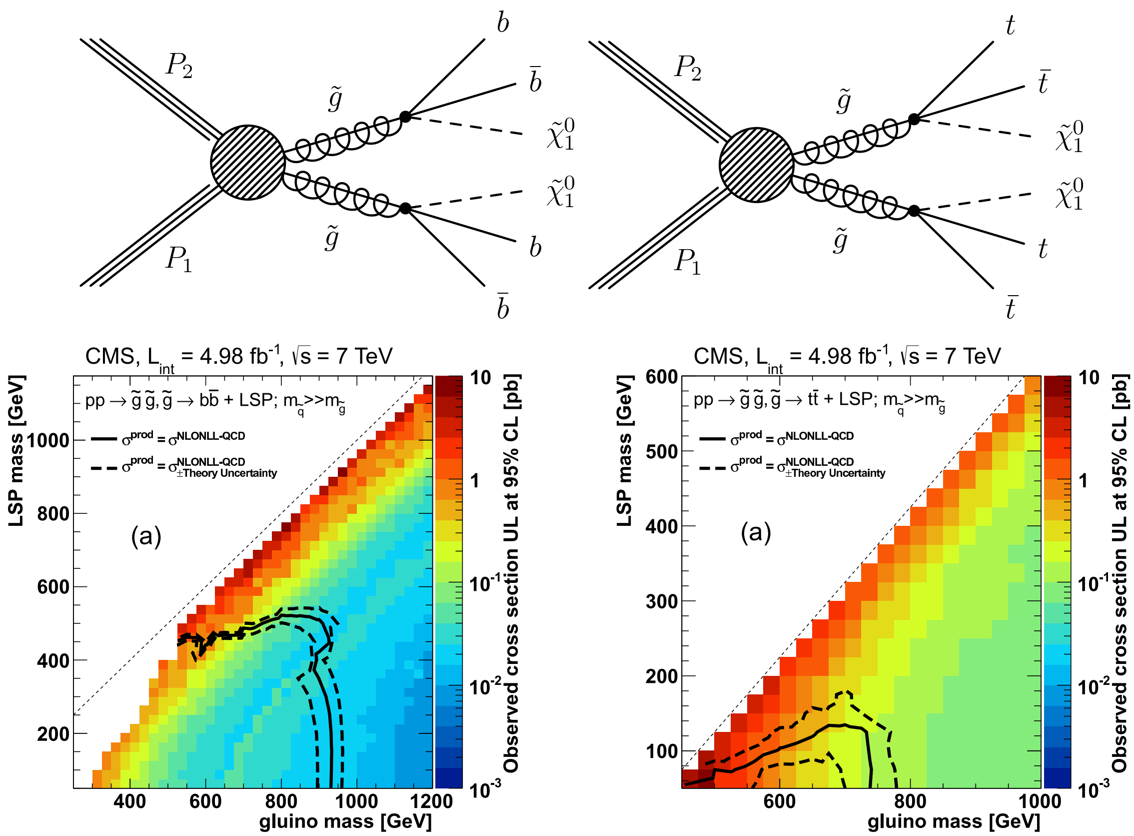

Figure 1.13: 95% CL cross section upper limits from the 7-TeV data for the T1bbbb (left) and T1tttt (right) simplified models. For each point, we choose the selection that yields the best expected cross section limit. The solid contour shows the 95% CL exclusion limits on the gluino and LSP masses using the NLO+NLL cross section for new physics. The dashed contours represent the theory uncertainties.

SUSY PAG's liaison to the speaker's committee, providing or filtering abstracts and reviewing talk drafts for conferences. Smith is responsible for facilitating the analyst's access to data sets, monitoring disk space usage and directing data sets to the appropriate Tier-2 sites.

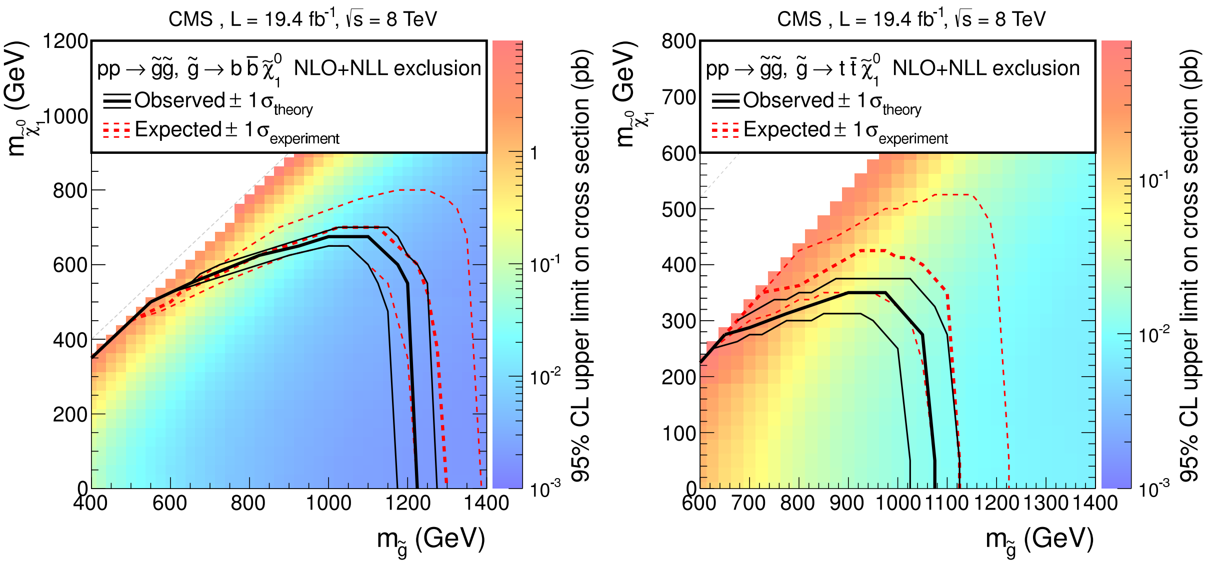

Figure 1.14: The 95% CL upper limits from the 8-TeV data on the (left) T1bbbb and (right) T1tttt new-physics scenario cross sections (pb) derived using the CL_s method. The solid (black) contours show the observed exclusions assuming the NLO+NLL cross sections, along with the ± 1 standard deviation theory uncertainties. The dashed (red) contours present the corresponding expected results, along with the ± 1 standard deviation experimental uncertainties.

4 Neutrino Physics

Faculty: Alysia D. Marino, Eric D. Zimmerman. Postdocs: Stephen J. Coleman, Robert A. Johnson, Graduate students: Scott Johnson, Andrew D. Missert, Tianlu Yuan.

4.1 Personnel

The neutrino physics effort at Colorado was started by Professor Eric D. Zimmerman in 2001. Assistant Professor Alysia D. Marino joined the University in January 2009. The group has been active in the past three years on MiniBooNE, T2K, and LBNE. The base neutrino effort encompasses MiniBooNE, T2K, and LBNE. In recent months, the group has joined the NA61/SHINE experiment at CERN as limited collaborators. A letter of intent on US participation in this experiment was recently submitted to DOE and a more formal proposal is planned for later this year.

Marino's program is supported by her Early Career Award for FY2013 and FY2014, but is closely associated with the base neutrino program and is therefore briefly described as well in this section.

In the past three years, postdoc Martin Tzanov has moved on to a faculty position at Louisiana State University. PhD students Michael Wilking and Robert Nelson have graduated and are now in postdoctoral positions at TRIUMF and Caltech respectively. As of summer 2013 the group supported by the base DOE grant consists of Zimmerman, one postdoc (Stephen Coleman), and one graduate student (Andrew Missert). Marino's Early Career Award also partially supports a postdoc (Robert Johnson) and a graduate student (Tianlu Yuan). Graduate student Scott Johnson began working with Marino in 2011 and is largely supported by University funds. Zimmerman was promoted to Professor in 2013.

Marino

Alysia Marino was not supported by this DOE grant. Therefore the efforts of her and her students and postdoc are only briefly described here.

Alysia Marino has been working in neutrino physics for the past 15 years, since her undergraduate thesis on the Borexino solar neutrino experiment. Her PhD thesis, which was awarded the 2006 APS Tanaka Dissertation Prize, was an analysis of the solar neutrino fluxes in the second phase of the Sudbury Neutrino Observatory, where NaCl was added to the detector to increase the sensitivity to neutral current interactions. In 2004 she became a Research Associate at Fermilab on the MINOS experiment, where her work included estimating the NC background to the ν_μ CC signal and serving as the Monte Carlo coordinator.

In 2006 Marino joined the T2K collaboration as a Research Associate at the University of Toronto. There she led the effort to design, produce, and install a beam monitor that uses transition radiation to determine the position and shape of the T2K proton beam, just before it strikes the target. This is a particularly high radiation environment making it difficult to deploy more conventional beam position monitors. This device was installed in Japan in the fall of 2008, and began operation in April 2009. A paper describing this device was published in NIM [113].

Since Marino's move to Colorado in Jan 2009, she has continued to work on T2K, but her focus has shifted to the ND280 off-axis near detector, and in particular to the pi-zero subdetector (P0D), which is a US responsibility. She also has served in the past as a convener of the ND280-Beam analysis group, and is currently a convener of the ND280 computing group. In 2010 she was granted a DOE Early Career Award, and later was selected to receive a Presidential Early Career Award for Scientists and Engineers.

Marino is particularly interested in the interplay between near detector measurements and beam uncertainties. Her group has begun an analysis in T2K of the ν_μ CC events originating within the P0D. Near detector measurements of the ν_μ rate are an important input for both the ν_e and ν_μ oscillation analyses, and potentially can help to constrain understanding of the beam systematic uncertainties. In 2009 she joined LBNE where she serves as the Deputy Project Manager for beamline measurements. Her particular focus on LBNE is on the design of muon monitors that will sit at the end of the beamline, and can potentially provide information about the absolute neutrino flux. Along these lines, she has recently joined the US effort on the NA61/SHINE experiment, a particle production experiment at CERN, where she hopes to contribute to analyses of measurements of hadron production in the T2K target and potential future measurements that would be important for reducing the neutrino flux uncertainties in LBNE.

Zimmerman

Professor Eric D. Zimmerman has been on the faculty at the University of Colorado since 2001, where he has worked primarily on the MiniBooNE (Fermilab E898/944) and T2K neutrino physics collaborations. Previous efforts included Fermilab experiments E815 (NuTeV) as a postdoc at Columbia, and E799/E832 (KTeV) as a graduate student at the University of Chicago. He also serves as Associate Chair for Graduate Studies in the Physics Department, which earns him periodic teaching releases: one of these was in Fall 2012, when he was a Visiting Scholar at TRIUMF working on T2K analysis.

The Zimmerman effort's major accomplishments in the past three years have been: 1) analysis and analysis leadership roles in the T2K neutrino oscilltion analyses; 2) completion and publication of two major neutrino cross-section papers in MiniBooNE [95, 96]; 3) construction of a spare Horn 2 for T2K (accomplished largely with Japanese funding).

4.2 MiniBooNE (E898/E944)

Faculty: Eric D. Zimmerman

MiniBooNE (Experiment 898/944 at Fermilab) is a short-baseline neutrino oscillation experiment that began collecting data in August 2002, and continued operations until the beginning of the 2012-13 lab-wide accelerator shutdown. The motivation for the experiment was to confirm or refute the controversial observation at LSND of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations at $\Delta m^2 \sim 1$ eV^2 [97].

Neutrino oscillation studies

In April 2007, the first result on $\nu_\mu \to \nu_e$ appearance (the "LSND effect") was presented [90]. This result was based on the 5.7×10^{20} protons on target received in standard running conditions from 2002 through 2005. The result was not easily consistent with LSND-type oscillations, although a significant excess of ν_e-like events was observed with reconstructed energy below 475 MeV [98]. The excess remains unexplained.

The Booster Neutrino Beam has operated primarily in antineutrino mode since early 2006, and the oscillation analysis results from 5.7×10^{20} protons were published in 2010 [99]. An excess of $\bar{\nu}_e$ candidates was seen in this data set as well, in this case consistent with LSND-like oscillations. The fit to the $E_\nu > 475$ MeV region (selected to avoid the low-energy excess) preferred a two-neutrino oscillation hypothesis over a background-only hypothesis at 99.4% confidence level. An update with

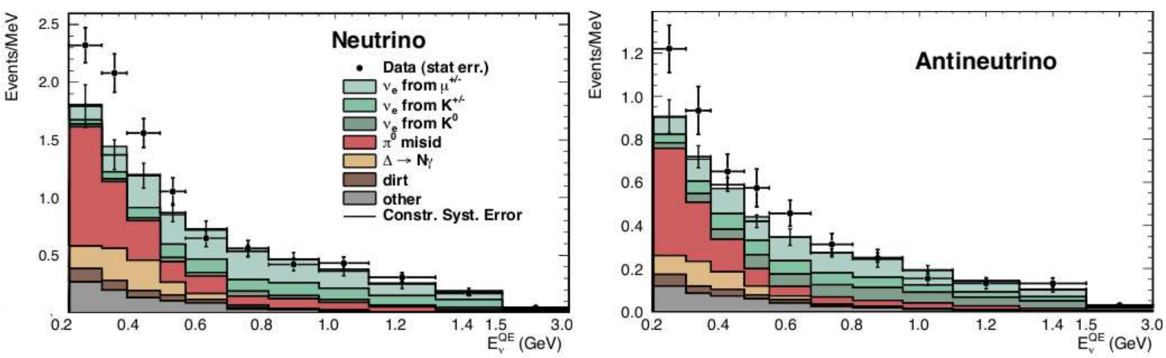

Figure 1.15: Signal candidates and background estimates for ν_e (left) and $\bar{\nu}_e$ (right) appearance using the full 2002-2012 MiniBooNE data sets.

50% more data was announced* in July 2011, and another [100] in July 2012 with the full data set collected before the 2012-13 Fermilab shutdown. The new data (Fig. 1.15) show fewer events in the high-energy region where an LSND-like signal would appear, but more events in the low-energy region. While the data remain consistent with LSND, the exclusion of the background-only hypothesis is weaker, with oscillations favored over background only at 91.4% confidence.

Other Colorado activities on MiniBooNE

Colorado has been an actively collaborating institution since 2001. In previous years, we led the analysis of the BooNE neutrino beamline and the operation and analysis of a novel beam monitoring device we built. An instrumentation paper on the device is in draft form and will appear this year. Zimmerman convened the collaboration's Kaon/Beam Analysis group, which produced neutrino flux predictions for all MiniBooNE analyses. We have also developed and maintained (through 2009) the collaboration's GEANT4 beam Monte Carlo. All production beam MC samples for MiniBooNE analyses were generated on the CU farms.

Since 2007, much of the efforts of the Colorado group have been directed toward using our unique data set to measure exclusive and inclusive medium-energy ν_μ cross-sections. These are some of the first measurements ever made with neutrinos in this energy range on nuclear targets. Our group's main cross-section results were published last year in back-to-back *Phys. Rev. D* papers [95, 96], each principally authored by a recently-graduated Colorado PhD student. Michael Wilking's analysis was on the differential cross-section of charged-current π^+ production. He developed a novel fitting technique that has accomplished the first known reconstruction of charged pions with hadronic interactions in a Cherenkov-type neutrino detector. The exclusive charged-current π^0 production cross-section was the subject of Nelson's PhD thesis in 2010; he developed MiniBooNE's first fitter designed to reconstruct a three-particle final state. Both results improve on previous experiments by more than an order of magnitude in statistics, allowing differential cross-sections (and, in the case of charged-current π^+, double-differential cross-sections) to be measured for the first time. The measured Q^2 distribution is shown in Fig. 1.16.

Tzanov has been the collaboration's analysis convener for all modes with pions. He gave an invited review talk on this physics topic at Neutrino 2010. Additionally, he is completing (at LSU) a separate analysis of inclusive charged-current hadron production using a new reconstruction

*Zimmerman presented the first announcement of this result at the PANIC'11 conference.

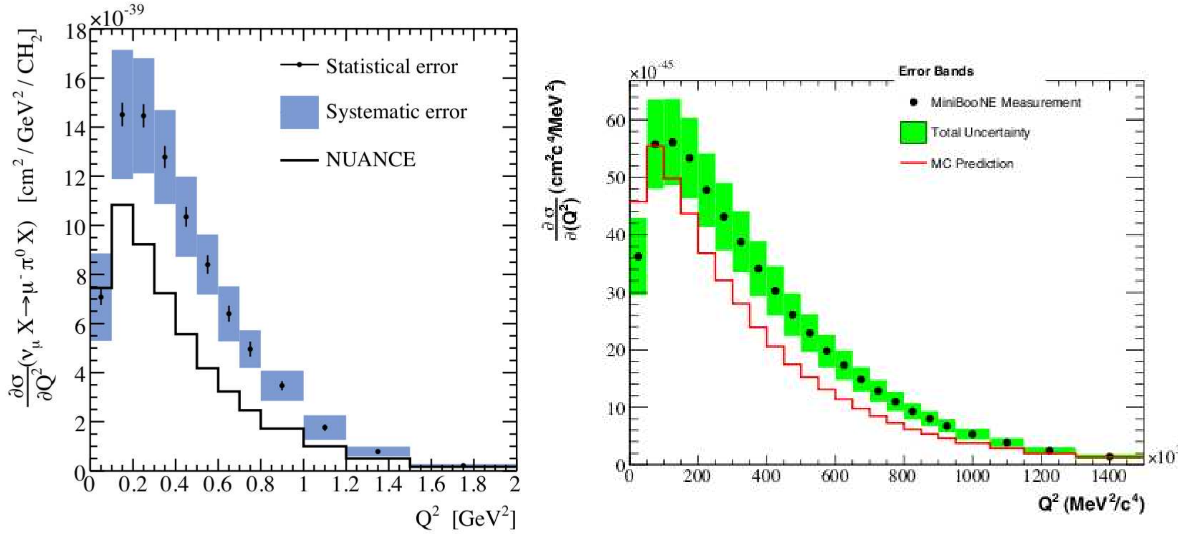

Figure 1.16: Left: MiniBooNE's measured Q^2 distribution for charged-current π^0 (left) and charged-current π^+ production. NUANCE model prediction shown as solid histogram in both plots.

optimized for measuring the neutrino energy in many exclusive channels. This is an effort to understand the low-energy turn-on of multipion production and deep inelastic scattering. As the total charged-current cross-section is used for normalizing many neutrino interaction models, this result will be of intense interest in the community. The first preliminary results were announced at NuFact 2012.

4.3 T2K Effort

Faculty: Alysia D. Marino, Eric D. Zimmerman. Postdocs: Stephen J. Coleman, Robert A. Johnson. Graduate students: Scott Johnson, Andrew D. Missert, Tianlu Yuan.

T2K, at the Japan Proton Accelerator Research Center (J-PARC), is the first experiment to use the off-axis beam technique to achieve a narrow-band neutrino flux at a far detector (the existing Super-Kamiokande). The main goal of the experiment is the measurement of θ_{13}. Colorado joined T2K in early 2004, and this effort is now the main focus of the neutrino program at Colorado.

T2K's first beam on target was received in April 2009, with 0.33×10^{20} protons received with the detector live between January and June 2010 ("Run 1"). A further 1.12×10^{20} protons were received on target in Run 2, which occurred from November 2010 to March 11, 2011 when the laboratory was damaged in the Great East Japan Earthquake Disaster. Repairs to the accelerator and beamline are now complete, and physics data collection resumed in March 2012.

In June 2011, T2K announced its first analysis results on the combined Run 1 + Run 2 data set. The paper was published in *Phys. Rev. Lett.* [101] last summer. T2K observed six $\nu_\mu \to \nu_e$ candidate events. The expected background was 1.5 ± 0.3, which has a probability of 0.7% of fluctuating to six or more events. This result was the most significant indication at the time that θ_{13} is nonzero. The latest analysis, with over 3×10^{20} protons on target, was presented at ICHEP 2012 in Melbourne (Fig. 1.17). With the new result, there are eleven candidate events and an expected background of 3.2 ± 0.4. The background-only p-value is thus reduced to 8×10^{-4}. T2K has also produced a measurement of ν_μ disappearance [102], and has found 2-3 sector mixing parameters consistent with other experiments.

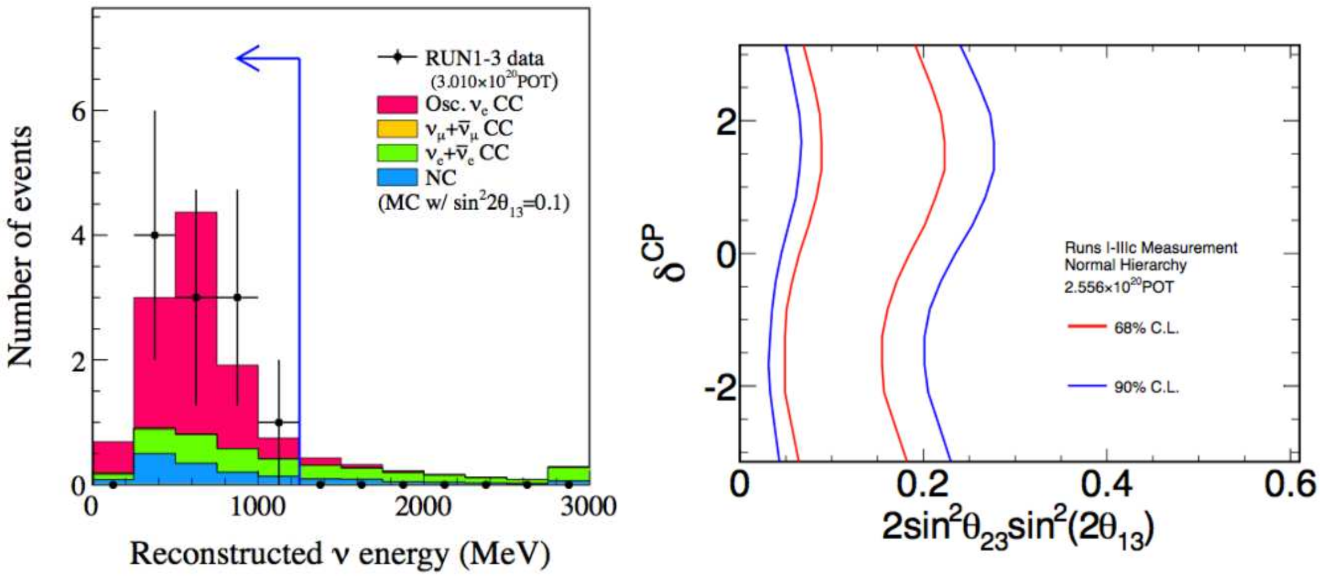

Figure 1.17: Left: reconstructed neutrino energy for oscillation $\bar{\nu}_e$ quasielastic scattering candidates in T2K. Right: oscillation allowed regions from T2K using the single-bin Feldman-Cousins analysis. Fit assumes $\Delta^2_{m_{32}} = 2.4 \times 10^{-3}$ eV^2 and $\sin^2\theta_{23} = 1$ and the normal hierarchy.

Zimmerman Effort on T2K

Hardware and operational tasks Our major hardware contribution to T2K was the second focusing horn in the secondary beam. The horn assembly occurred at CU in the late spring and early summer of 2008. The horn was installed and commissioned in 2009 and has continued to operate since then. A spare horn was built with KEK funds in 2012 and delivered in 2013.

CU also developed and built the magnetic field measuring system and has been in charge of field mapping for all T2K horns. The Colorado group contributed to the post-earthquake reconstruction by mapping the fields on the replacement Horn 1 as well as the accelerated production of a spare Horn 2.

Coleman, Missert, and Zimmerman fulfill their shift duties at Super-Kamiokande.

Analysis tasks Our analysis efforts at present are directed toward the next generation of the oscillation analysis. Postdoc Coleman was heavily involved in the initial ν_e appearance analysis, where he led one of the collaboration's three oscillation analyses. This work involved the single-bin counting experiment analysis, which was one of three analysis methods that T2K pursued. The other two analysis methods employed unbinned log-likelihood methods with one or two variables related to the reconstructed neutrino energy. The single-bin analysis is the only one of the three that utilizes the Feldman-Cousins [103] method to determine correct confidence intervals.

The Feldman-Cousins treatment of the single-bin analysis has proved to be a useful check on the allowed regions produced by the other two analyses. As we accumulate more data and our lower limits on $\sin^2(2\theta_{13}) = 0$ become more significant, we must be careful of our coverage, particularly near the low end. In plots of $\Delta\chi^2$ vs. $\sin^2(2\theta_{13})$, in particular, the Feldman-Cousins approach shows that proper coverage is not guaranteed when assuming a constant $\Delta\chi^2$ when drawing 68% C.L., 90% C.L., or 3σ allowed regions. This analysis has shown the collaboration that lower bounds drawn at 3σ significance are overly conservative, and may understate the significance of our result for some values of δ_{CP}.

GRA Missert is an expert on the T2K beam Monte Carlo. He has made detailed calculations and measurements of horn field perturbations and implemented them in the Monte Carlo. A notable accomplishment is the prediction and subsequent observation of nonzero magnetic fields in the target region due to azimuthal current asymmetries in the horn. While maintaining his work on the beam simulation, Missert made improvements to the far detector Monte Carlo enabling the inclusion of full neutrino parent history in simulated SK neutrino events.

Missert, Coleman, and Zimmerman directed much of their analysis effort in 2012 toward the development of a new SK event reconstruction, in collaboration with T2K colleagues in Canada (including Michael Wilking, a former CU graduate student). Zimmerman was funded by TRIUMF as a Visiting Scholar in Fall 2012 in order to develop this analysis and organize our collaboration with the Canadian groups. The first results of this effort, a more powerful replacement of the previous algorithm for distinguishing neutral-current π^0 decays from charged-current ν_e interactions, will be first included in official summer 2013 results. We have begun preparing upgrades to the new reconstruction software for future analyses, where it will replace the entire historical SK reconstruction code.

From 2007-09, Zimmerman served a two-year term as one of the three co-conveners of the T2K global analysis group (a position roughly equivalent to analysis coordinators in other experiments). He chaired the internal review of the ν_e appearance oscillation analysis in 2011, and served as the beam expert on the review of the ν_μ disappearance analysis.

Marino Effort on T2K

Marino's T2K efforts are only briefly described here since she was not supported on this grant. Over the past 3 years, Marino's efforts on T2K have centered on the P0D [104] of the ND280 off-axis near detector [105] at J-PARC. The T2K near detector is largely composed of plastic scintillator while Super-Kamiokande is filled with water. The P0D has 50 water bladders that can be filled and drained to allow for a comparison of the neutrino interaction rates on water and carbon. Marino's group has participated in the testing, calibration, installation and monitoring of the water level sensors, which are used to look for leaks and to determine the mass of water in these bladders for physics analyses [106]. Marino also served as an editor for the recently-published paper that describes the pi-zero subdetector [104]. She coordinated the bi-weekly T2K US analysis meetings for 2 year, chaired the internal review committee for T2K beam systematic errors in for the 2012 analyses, and served on the review committee of the new ν_e appearance analysis that was presented in the summer of 2012, and will again serve on the review committee for this analysis of the summer 2012 results.

Marino is one of the near detector computing conveners, who are responsible for coordinating the production and distribution of reconstructed data and Monte Carlo (MC) simulated files to the collaboration. Colorado is also a second-tier computing site for T2K. Since early 2012, it has been used to generate official near detector MC files for use by all of the collaboration. To date general MC files have been generated at Colorado at ~30x the data statistics, and additional specialized samples (such as CC π^+ events) have been simulated as well.

Robert Johnson served on the global reconstruction task force, and moved on to become one of the reconstruction conveners for the near detector. The reconstruction group has made a big push over the last year to improve the global reconstruction package that combines information from all of the various subdetectors. There will continue to be major improvements in this area over the next year.

At present, postdoc Robert Johnson and second-year graduate student Tianlu Yuan are collaborating on an analysis of ν_μ events originating in the Pi-Zero subdetector (P0D) of the near detector. A preliminary version of this work has been documented in a T2K technical note [107]. The plan for this analysis over the next year is to upgrade this analysis to use the newer reconstruction software, increase the number of bins to obtain more detailed spectral information, and possibly to determine the data/MC ratio on water only, by doing a comparison of the data periods where the P0D water targets were filled with water or air. The ultimate goal is to then use these results on the interaction rate in water as an input to the oscillation analysis. An understanding of the ν_μ rate on water in the near detector is an important constraint for the both the ν_μ disappearance and the ν_e appearance analyses.

Undergraduate Bryan Barnhart worked with Marino's group in the summer of 2012 on a search for $\bar{\nu}_\mu$ events in the P0D.

4.4 LBNE Effort

Faculty: Alysia D. Marino, Eric D. Zimmerman. Postdocs: Stephen J. Coleman, Robert A. Johnson. Graduate student: Scott Johnson.

Our participation in the Long Baseline Neutrino Experiment (LBNE) began approximately four years ago. This proposed experiment will send a beam of muon neutrinos from Fermilab to a large liquid argon TPC far detector located 700-1300 km away. The physics goals including making precision measurements of $\nu_\mu \to \nu_e$ appearance and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance to determine the mixing angles, the mass hierarchy, and to search for CP violation in the neutrino sector.

The Colorado LBNE effort has concentrated on beamline measurements and specifically on the development of beam monitoring in the region downstream of the absorber. Muons are produced inside the decay pipe from the same pion decays that produce the ν_μ's, and therefore are correlated with the neutrino flux. Measurements of the muons exiting the absorber would be used to monitor the beam profile and stability, and would place a constraint on the absolute neutrino flux at high energies that is independent of the uncertainties on neutrino interaction cross sections. At the time of writing, the LBNE project is undergoing a major re-scoping and reconfiguration and our level of activity and individual tasks may change significantly. However, it should be noted that secondary beam monitoring will likely be critical since the selected reconfiguration option for LBNE has no near neutrino detector in the first phase. For this reason, beamline measurements, including the in-situ measurements of the muons exiting the decay pipe described here and external hadron production measurements (which will be discussed in Section 4.5), will be especially important for constraining the predicted neutrino flux at the far detector.

Marino served as the deputy project manager for beamline measurement in LBNE through the CD1 process, and this included many contributions to LBNE reviews and to the conceptual design report [114]. Her group is also developing a conceptual design for a threshold gas Cherenkov detector to measure the muon spectrum. Over the past 2 years, postdoc Rob Johnson and undergraduate thesis student Craig Pitcher developed a GEANT4 simulation for a proposed gas Cherenkov detector for the LBNE muon monitors. Based on this work, a conceptual design has been developed. The muons enter a region of dense (possibly freon or argon) gas Cherenkov photons are produced. The light is bounced off of mirrors towards a photo-sensor that sits in a lower radiation environment. Several different mirror configurations were examined, including spherical and conical mirror shapes. But flat mirrors were found to be adequate, and are favored because of their simplicity. Varying the gas density will allow for the photon measurements to be sensitive to different parts of the muon energy spectrum[108]. Undergraduates Craig Pitcher and Sebastien Tawa (both supported by University funds) also worked closely with Marino and R. Johnson in 2011 on FLUKA and GEANT4 simulations of the muon range in rock, to determine the shortest tolerable distance between the end of the LBNE absorber and the LBNE near detector hall before the decay pipe muons become a significant background to Near Detector events. This work was summarized in a technical note [109].

An array of ionization counters is also proposed to monitor the stability of the LBNE neutrino beam direction and size on a spill-by-spill basis. In the fall of 2011, grad student Scott Johnson worked with Marino on toy simulations to determine the optimal layout for these counters, and verified that this layout should be capable of monitoring the beam directional stability to the required level of stability.

Zimmerman, with undergraduates Aaron Bercellie, Craig Pitcher, and Daniel Poulson, has begun conceptual design of counters to detect the decays of stopped muons ("Michel decays") in the region downstream of the beam absorber. This novel detection method is designed to overcome some of the limitations of traditional monitoring of through-going muons. Stopped muons at a particular location sample a single range and therefore a narrow energy band, rather than an integral above a threshold as with through-going muons. The ability to gate off the detector during the beam pulse, while enabling it several muon decay lifetimes later, will allow the detectors to operate in a low-rate environment. This will allow detection of individual muons and therefore a precise normalization. By contrast, prompt muon detectors observe a collective analog ionization signal from a high rate of through-going particles and the absolute muon flux is generally not well understood. Finally, the ability to fit for the muon lifetime will enable us to distinguish cleanly between actual muons and backgrounds from neutrons or other particles. Due to the shorter lifetime of μ^- in material compared to μ^+, the later observed decays will be primarily μ^+. It may also be possible to measure μ^- rates by placing carbon targets for μ^- capture into the detector systems and observing the 20 ms decay lifetime of the resulting ^{12}B.

4.5 Effort on NA61

Faculty: Alysia D. Marino, Eric D. Zimmerman. Graduate student: Scott Johnson.

Marino and Zimmerman were authors on a recent letter of intent that was submitted to the DOE and NSF for US participation in the NA61/SHINE [110] experiment. There is strong overlap between this effort on NA61 and the existing efforts on T2K and LBNE. The NA61 experiment is composed of a large-acceptance hadron spectrometer at CERN that is being used to the study hadron-nucleus and nucleus-nucleus collisions. Precision calculations of neutrino fluxes are dependent on improved knowledge of the hadron production cross sections for pions and kaons that result from proton-nucleus collisions inside the neutrino beam target. The NA61 experiment has already published results for the π and K production resulting from the interactions of 31 GeV/c protons on a thin carbon target [111] [112]. These measurements are extremely valuable to the T2K experiment and have greatly reduced the uncertainties on the neutrino flux and will continue to improve these uncertainties in the future.

Consistent with the group's interest in beamline measurements for LBNE, we are very interested in establishing a collaboration with the NA61 collaboration that would benefit current and future Fermilab neutrino beams. This letter of intent includes the possibility of making future thin target measurements of high energy protons (and potentially also pions) on a carbon target (and possibly also an aluminum target) in 2014 and 2015. These cost-effective measurements would greatly reduce the uncertainties on flux predictions for the LBNE beamline, as both a proposed new beamline to

Homestake and the existing NuMI beamline begin with 120 GeV/c proton striking a thick graphite target.

In the summer of 2012 the NA61/SHINE collaboration generously allowed us to take several days of test beam data at CERN with a 120 GeV beam on thin carbon target. Marino and her graduate student Scott Johnson traveled to CERN this summer, took NA61 detector shifts, and used this opportunity to learn more about the detector, hardware, and analysis framework for the experiment. While still in the early stages, Scott has started to examine reconstructed event distributions in the NA61 data and is working on a calibration package to determine the residual position corrections that need to be applied to the reconstructed track positions.

Chapter 2

Theory Group (Task B and T)

Senarath P. de Alwis, Thomas A. DeGrand, Oliver DeWolfe,
Anna Hasenfratz, and K. T. Mahanthappa

Contents

1 Overview of the theoretical program

We are presently five theorists. T. DeGrand and A. Hasenfratz do lattice gauge theory, S. de Alwis studies string phenomenology and cosmology as well as theories of supersymmetry breaking, O. DeWolfe studies string theory and the gauge/gravity correspondence, and K. T. Mahanthappa studies geometrical CP violation with discrete family symmetries combined with grand unification. We have one postdoc, David Schaich, who does lattice gauge theory. His appointment will run through August 2013. In the last three-year grant period three theory graduate students received their PhD degrees:

- M. Brown (2010) now has a faculty position at Kentucky State
- C. Rosen (2012) has a postdoctoral research position in Crete
- K. Givens (2012) is working for CitiBank.

A. Cheng (lattice) and O. Henriksson (strings) are continuing graduate students. Graduate student Greg Petropolous (lattice) is ending his third and final year of a DOE Graduate Fellowship.

2 Research of T. DeGrand

My research is focused on the nonperturbative behavior of theories of gauge fields and fermions, mostly using lattice techniques. In the last few years I have concentrated three areas: studies of candidate theories for beyond - Standard Model physics, studies of $\mathcal{N} = 4$ super Yang Mills theory, and on simulations of QCD with many colors.

2.1 QCD

My pure QCD work has been as a co-author of the Quark Model minireview of the Review of Particle Properties of the Particle Data Group. In 2012 I was asked to write a new longer summary of lattice spectroscopy, including excited states, exotics, and glueballs in addition to the usual lightest mesons and baryons. I will continue to update this article annually.

One QCD related project is my discovery that the correlation functions we use in QCD to extract masses, call them $C(t)$, are log-normally distributed (data for $\log C(t)$ is distributed as a Gaussian). This was inspired by a talk by David Kaplan[115] at Lattice 2011, who described the same behavior in simulations of unitary Fermi gases. I discovered that all my QCD data sets for ordinary quantities, like meson and baryon correlators and Wilson loops for potentials, were log-normal distributed, too. A paper on this sighting[116] was published in Physical Review D.

2.2 Systems which are similar to QCD

Replacing the "3" of color $SU(3)$ by "N" and then taking N to infinity has a long history in the (continuum) phenomenology of the strong interactions, dating back to 't Hooft in 1974. There is also a small literature of lattice simulations, mostly aimed at pure gauge theory. But nobody until now has looked at baryons in large N. They seem to be fascinating objects, either viewed as many-quark states or as topological objects in effective theories of mesons. In 2012 I wrote the first paper ever, on lattice results for baryon spectroscopy in large-N QCD [117]. The major physics

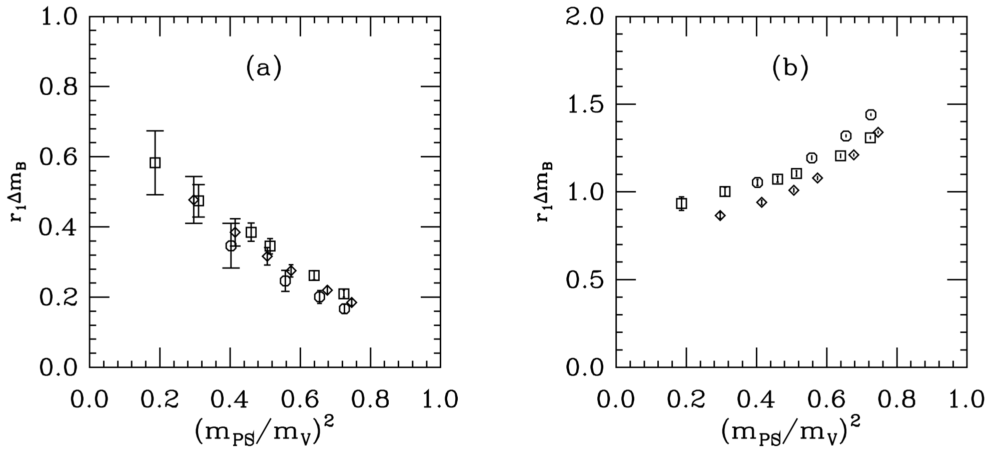

Figure 2.1: (a) The $J = N/2$ vs $J = N/2 - 1$ mass difference in the $SU(3)$, $SU(5)$, and $SU(7)$ multiplets, shown respectively as squares, diamonds, and octagons, gives B in Eq. 2.1. (b) A different combination of masses gives A. r_1 is a Sommer parameter, $1/r_1 \sim 600$ MeV.

result was my observation of a rotor spectrum: the mass of a two flavor (degenerate mass), N color baryon of angular momentum J is well described by the simple formula

$$M(N, J) = NA + \frac{J(J+1)}{N} B \tag{2.1}$$

where A, the "constituent quark mass," and B are smooth functions of the current quark mass and have typical hadronic sizes of a few hundred MeV. Combinations of data which give the A and B terms as a function of quark mass are shown in Fig. 2.1.

Large-N baryons are a completely new venue for lattice studies. These first simulations did not have to be high quality to expose simple and (hopefully) interesting physics. Currently, I am studying flavor $SU(3)$ states. There are many papers with predictions for mass relations. These papers make specific choices about the large N baryons which are to be compared to the real ($N = 3$) world. On the lattice, I can compute the mass of almost any ground state baryon, giving synthetic data for many more predictions.

2.3 Systems which are probably not like QCD

Theories which replace the fundamental Higgs with a composite object, a bound state of new fermions with a new gauge interaction, are generically called "technicolor." The requirements of phenomenology, namely chiral symmetry breaking and a spectrum of new particles, are nonperturbative and are perhaps QCD-like, so a number of lattice theorists began to do simulations on possible candidates for beyond-Standard Model physics.

To be compatible with precision electroweak constraints, a successful theory must "walk:" its beta function must be small. This can be achieved by increasing the number of fermionic degrees of freedom. However, if the number of degrees of freedom becomes too large, the theory crosses over from confinement to a phase where (for massless fermions) correlation functions decay algebraically. The system is said to be "inside the conformal window" and the running gauge coupling constant flows into an infrared attractive fixed point (IRFP). Being in this phase disqualifies the theory as a technicolor candidate. There are no technipions to be eaten.

In addition, the mass anomalous dimension γ_m, which determines the running of the mass parameter

$$\mu \frac{dm(\mu)}{d\mu} = -\gamma_m(g^2)m(\mu), \tag{2.2}$$

must be large to generate phenomenologically interesting fermion masses while avoiding too-large strangeness-changing neutral currents.

Techniques for studying these theories include doing spectroscopic studies or measuring coupling constants which can be cast as expectation values of observables. I have worked with both methods.

All simulations are dominated by the slowly-running coupling. It is easy to see that this is expected behavior. The one-loop beta function for the change of the inverse coupling under a scale change s is

$$\frac{1}{g^2(s)} - \frac{1}{g^2(1)} = \frac{b_1}{8\pi^2}\log s + \dots. \tag{2.3}$$

In three-flavor $SU(3)$, $b_1 = 9$ and in 12 flavor $SU(3)$, $b_1 = 3$, so that the equivalent scale changes in the two theories, for an equal change in coupling, are $s_{12} = s_3^3$. In ordinary QCD, the coupling runs from weak at a distance of 0.1 fm to strong at a distance 1.0 fm, or over $s = 10$. If the 12 flavor theory were similar, the same change in coupling would require $s = 1000$. It is hard to get a large aspect ratio s from a set of numerical simulations at a single set of bare parameters. Therefore, whether or not a running coupling in one of these many-fermion theories actually has an IR fixed point, it runs so slowly that for all practical purposes its running can be neglected. Then the zero mass limit is effectively conformal. Depending on how the simulation is done, this can be a bad thing or a good thing. I think I and my collaborators have been quite successful in exploiting this feature.

In a spectroscopy calculation, when one ignores the (slow) running of the coupling, the system is "effectively conformal." In infinite volume, tuning the fermion mass to zero causes the correlation length (inverse of any hadron mass) to diverge algebraically,

$$\xi \sim m_q^{-\frac{1}{y_m}}, \tag{2.4}$$

where $y_m = 1 + \gamma_m(g_*)$.

However, no simulation is ever done in infinite volume. The system size L is also a relevant parameter since the correlation length only diverges in the $1/L \to 0$ limit. When the correlation length measured in a system of size L (call it ξ_L) becomes comparable to L, ξ_L saturates at L even as m_q vanishes. However, if the only large length scales in the problem are ξ and L, then overall factors of length can only involve ξ and L. For the correlation length itself, this argument says that

$$\xi_L = LF(\xi/L) \tag{2.5}$$

where $F(x)$ is some unknown function of ξ/L. A somewhat more useful version of this relation invokes Eq. 2.4, to say

$$\xi_L = Lf(L^{y_m}m_q). \tag{2.6}$$

One uses this to find y_m by taking data at many masses and L's and varying y_m to collapse the data onto a common curve.

I think I was the first in the lattice BSM field to exploit this technique (although it is a standard result from the literature of critical phenomena). I applied it first [118] to $SU(3)$ with $N_f = 2$ flavors of sextet representation fermions. In 2011 [119] I revisited the technique in an analysis of

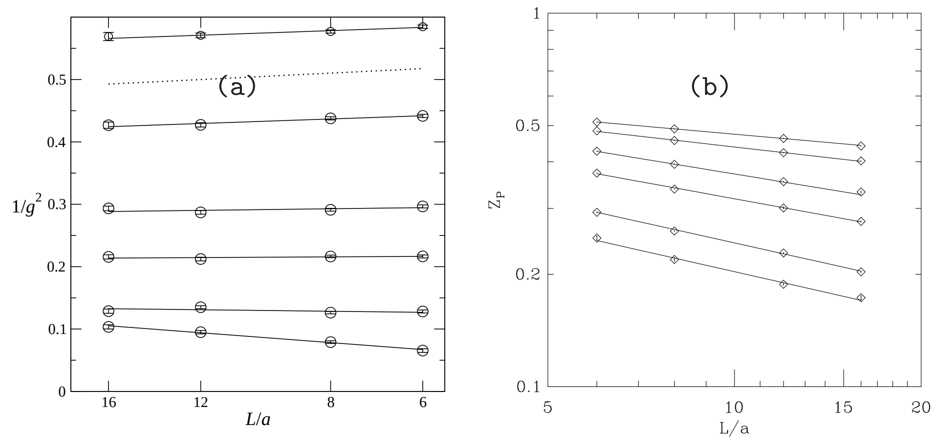

Figure 2.2: (a) SF inverse coupling $1/g^2(L)$ vs $\log L$ in the SU(2) theory. Lines are linear fits to data at fixed bare coupling. The beta function is the slope of each line. The isolated dotted line is the one-loop slope. (b) Pseudoscalar renormalization constant $\log Z_p$ vs $\log L$ for the same simulation points. γ_m is minus the slope of each line.

12 fundamental flavor $SU(3)$ data generated by Ref. [120]. It gives y_m (and hence γ_m) with rather large uncertainties. Other groups analyzing spectra are slowly beginning to do finite size scaling analyses of their data.

We have had much more success directly measuring a beta function and γ_m. This is done using a variation of the background field method called the "Schrödinger functional." The box size L defines a scale for a running coupling, which is a derived quantity related to a lattice expectation value. Measuring this $g^2(L)$ at several L's gives an integrated beta function. When the coupling runs slowly, the slope of $1/g^2(L)$ versus $\log L$ gives the beta function directly (recall Eq. 2.3.) We measure γ_m from the $L-$ variation of the pseudoscalar current renormalization factor. Because $g^2(L)$ runs so slowly, we can take γ_m from a straight-line fit to $\log Z_P(L)$ vs $\log L$.

We chose our particular set of models because some phenomenologists (Saninno and collaborators) preferred them as technicolor candidates and because we wanted to explore the unexplored.

We illustrate our raw data with results from the SU(2) study shown in Fig. 2.2. Fig. 2.3 displays our results for the beta function and $\gamma_m(g^2)$. Note how the mass anomalous dimension reaches a plateau at strong coupling. Even though our determination of the IRFP g_*^2 has large uncertainty, the weak dependence of γ_m on g^2 allows for a tight determination of the anomalous dimension at the IRFP, $\gamma_m(g_*^2) = 0.31(6)$.

We studied the following systems:

- $SU(2)$ with two adjoints: We observed an IRFP and measured a small γ_m [121].
- $SU(3)$ with two sextets: We observed that the beta function became small and measured a small γ_m [122].
- $SU(4)$ with two decuplets: We observed that the beta function became small and measured a small γ_m [123].

In the end, none of these models were technicolor candidates, because γ_m was too small.

We are completing work on two additional systems:

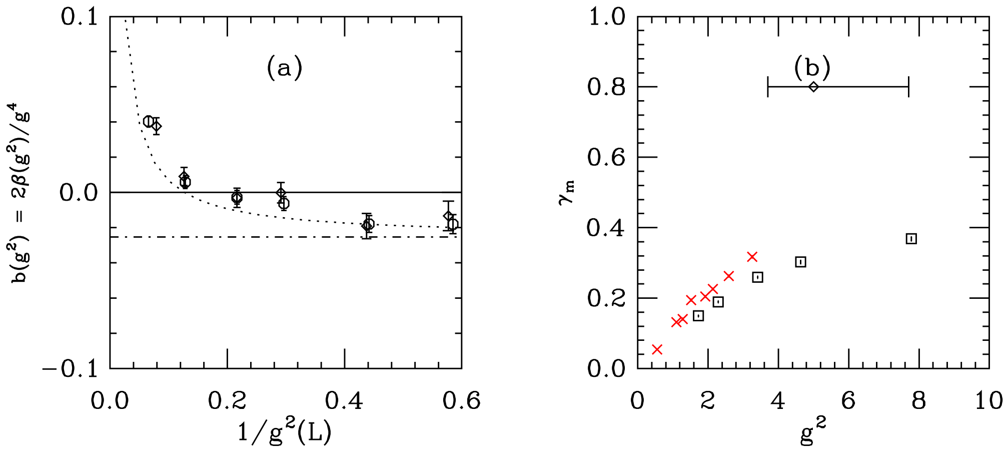

Figure 2.3: (a) Beta function for the inverse SF coupling in the SU(2) theory. The curves are the lowest-order and two-loop beta functions. Squares are fits to $L \geq 6$, octagons to $L \geq 8$. (b) Mass anomalous dimension $\gamma_m(g^2)$ from a linear fit to the $\log Z_p$ vs $\log L$ data, shown as squares. The horizontal bar at the top marks our result for g_*^2. The crosses are the data of Bursa *et al.*, analyzed with the same linear fit.

- $SU(3)$ with $N_f = 2$ adjoint flavors. We suspect it is conformal. There is a literature (Kogut, et al; Karsch and Leutgemeyer) claiming that it is confining with separated deconfinement and chiral-restoration transitions.

- $SU(4)$ with $N_f = 6$ antisymmetric representation flavors. Nothing is known about these systems. We suspect that $N_f = 6$ is barely conformal.

We have 3.3M service units through USQCD and 7.8M service units through the NSF XSEDE program for the two projects. These kind of calculations require simulations on many different lattice sizes. They mate well with the computing resources at Colorado, since we did the small volumes locally and the big ones on remote supercomputers.

2.4 $\mathcal{N} = 4$ Super Yang Mills on the lattice

Finally, I am working with S. Catterall (Syracuse) and Poul Damgaard (Niels Bohr Institute) doing lattice simulations of $\mathcal{N} = 4$ Super Yang Mills theory. This is a magical theory with many theoretical applications (to name one, it is the CFT of AdS-CFT). It is believed that its beta function is exactly zero. The techniques for putting the theory on the lattice while leaving one unbroken supersymmetry generator and the remaining ones broken by irrelevant operators are due to Catterall, Kaplan, Ünsal and others (for a review see Ref. [124]). We are presently doing simulations with USQCD and Danish resources and are looking at global observables, as indicators of possible phase transitions, and the potential. A paper [125] with our first results appeared last fall. This is an absolutely wide open area and promises to be exciting.

3 Research of Anna Hasenfratz

I research strongly-interacting quantum field theories using non-perturbative lattice gauge theory techniques, focusing on potential applications to physics beyond the standard model (BSM). In the past three years I focused on SU(3) gauge theories with many light fermions in the fundamental representation. In addition to the theoretical value of gaining non-perturbative understanding of strongly-coupled systems beyond QCD, these investigations are also motivated by the possibility that new strong dynamics may underlie electroweak symmetry breaking or describe the dark matter of the universe. Any realistic model of BSM physics must reproduce the low-energy phenomenology successfully described by the standard model, including now the 125 GeV boson recently discovered by the ATLAS and CMS experiments at the LHC [126, 127]. This discovery rules out "Higgsless" models of new strong dynamics, and requires that any strongly-coupled model predict a suitably light and narrow composite state to remain viable. Non-perturbative lattice calculations have a crucial role to play in this undertaking.

The research discussed below was carried out during the past couple of years and partially was done in collaboration with David Schaich, postdoctoral assistant, and Anqi Cheng and Gregory Petropoulos, graduate students.

3.1 Overview: Many-fermion systems on the lattice

Our recent research into lattice gauge theories beyond QCD has focused on SU(3) models with $N_f = 4$, 8, 12 and 16 light fermion flavors in the fundamental representation. While most of these models are known not to be phenomenologically viable, systematic investigation of both QCD-like systems ($N_f = 4$) and IR-conformal systems ($N_f = 16$) is crucial. The field of BSM lattice studies is still young, but it has already become clear that methods developed for lattice QCD are not always effective for many-flavor systems. We have had to re-evaluate our methods and develop new techniques that are better suited to studying many-flavor systems and exploring the IR-conformal dynamics that emerge as N_f increases. The methods that we have developed, tested and evaluated for these SU(3) gauge theories will assist future investigations of more phenomenologically promising models.

The 12-flavor system has attracted the most attention so far, and provides a valuable illustration of the challenges of studying nearly-conformal dynamics on the lattice. Different groups using different lattice actions and lattice methods have arrived at contradictory conclusions about the infrared dynamics of this system (recent references include [120, 132, 133, 134, 135] and earlier works are reviewed in Ref. [136]). While our own results from the several complementary studies discussed below consistently indicate that the 12-flavor model is IR conformal, we believe it remains important to continue working to resolve the present discrepancies. We need to better understand the systematic issues affecting these different lattice methods, if we are to have full confidence in results from lattice studies of strongly-interacting theories beyond QCD.

Lattice actions and lattice artifacts

In our work we address systematic lattice artifacts by using a highly-improved lattice action. Minimizing lattice artifacts is at the heart of every improved action and is especially important for BSM studies, where the many fermionic degrees of freedom require that we work at strong couplings where lattice artifacts can be severe. The first MCRG studies of many-flavor systems used the usual $\beta_A = 0$ (Sec. 3.2), in Ref. [132] I showed that these systems possess a line of first-order transitions and spurious UVFP in the fundamental–adjoint plane. These lattice artifacts did not allow MCRG calculations to be performed at strong enough couplings β_F to resolve the systems' infrared dynamics. Changing the gauge part of the lattice action to include a negative adjoint coupling $\beta_A = -0.25\beta_F$ moved the simulations away from the spurious UVFP and made it possible for MCRG analyses to obtain clear results. We now use $\beta_A/\beta_F = -0.25$ in all of our studies.

In addition to improving the gauge action, the fermions must also be improved. We use nHYP-smeared staggered fermions that significantly reduce lattice artifacts but are local enough to be used at the coarse lattice spacings corresponding to strong couplings. In our recent work [137] we studied this system at such strong couplings that the original nHYP action from Ref. [130] developed numerical problems, an issue that also affects other groups' calculations with different lattice actions. We found that a slight change in the HYP smearing parameters resolved the numerical problems, and we now use these modified smearing parameters in all of our studies.

3.2 Monte Carlo renormalization group studies

MCRG approach

Monte Carlo renormalization group methods, based on Wilson's renormalization group (RG) approach, have been used to study the critical behavior and RG β function of many spin models and pure-gauge systems. In Refs. [138, 139, 132] I redeveloped the MCRG two-lattice matching technique to study many-flavor BSM models. By matching blocked actions, the method predicts pairs of couplings (β_F, β'_F) where the lattice correlation length differs by a factor of 2, $\xi(\beta_F) = 2\xi(\beta'_F)$. The bare step scaling function, defined as $s_b(\beta_F) = \beta_F - \beta'_F$, is the integral form of the RG β function and contains the same information. $s_b(\beta_F)$ has the opposite sign of the RG β function and vanishes at fixed points.

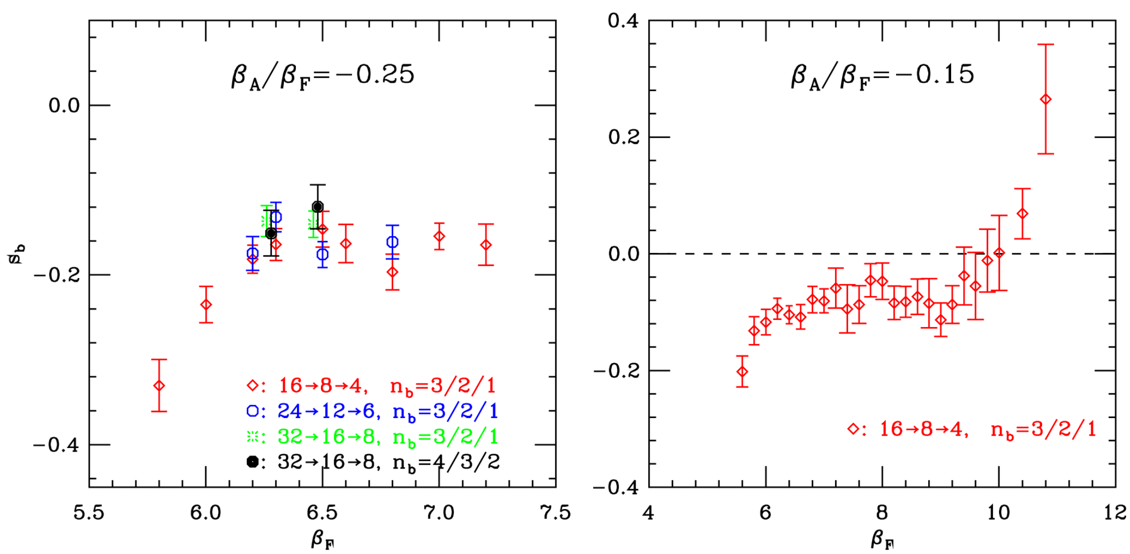

Figure 2.4: MCRG results for the 12-flavor model, from Ref. [140]. Left panel: the bare step scaling function with the $\beta_A/\beta_F = -0.25$ action. Different volumes and blocking levels all predict a consistent, negative step scaling function, implying an IR fixed point. Right panel: the bare step scaling function with the $\beta_A/\beta_F = -0.15$ action explicitly shows the fixed point.

The success of MCRG analyses depends on careful control of finite volume effects as well as optimization of RG blocking schemes. Optimization determines how quickly the RG flow reaches the renormalized trajectory that passes through the fixed point. However, optimization produces results for $s_b(\beta_F)$ that use a different scheme at each coupling β_F, and thus do not correspond to a unique RG β function.

Fig. 2.4 from Ref. [140] shows the bare step scaling function with two different ratios β_A/β_F. The left panel ($\beta_A/\beta_F = -0.25$) illustrates that different lattice volumes and different blocking levels predict a consistent, negative, step scaling function in the investigated range of β_F. Since the step scaling function is positive at asymptotically weak couplings, $\beta_F \to \infty$, this result implies the existence of a zero in the RG β function. The right panel ($\beta_A/\beta_F = -0.15$) shows the step scaling function for only one matching volume, but with the infrared fixed point explicitly visible. The two panels of Fig. 2.4 together give strong evidence that the 12-flavor system is IR conformal.

Wilson flow MCRG approach

Our current work aims to further improve MCRG analyses by combining this method with a form of continuous smearing known as the Wilson flow. Since the Wilson flow analysis does not require dedicated simulations, and the observable it uses tends to have small statistical errors, the approach appears very promising. However the perturbative basis of the Wilson flow limits the theoretical validity of this approach in strongly-coupled systems, especially on the strong-coupling side of an infrared fixed point.

Since MCRG methods are based on Wilson's non-perturbative renormalization group approach, they do not suffer from this limitation. Our goal is to use the Wilson flow to efficiently remove short-distance UV fluctuations, before performing MCRG analysis. The removal of lattice artifacts by the Wilson flow moves the system closer to the renormalized trajectory, which make it possible to carry out the MCRG analysis without optimizing the RG blocking scheme. Our preliminary explorations of the proposed technique show that are able to follow the renormalization group flow and identify the infrared fixed point in the 12-flavor case. In addition we are able to predict the scaling dimension of the irrelevant gauge coupling, an important quantity when analyzing this system. Our continuing investigations into MCRG methods will form a major part of Gregory Petropoulos's PhD research.

3.3 A novel phase in 12 and 8 flavor systems

With MCRG we study the renormalization group properties of the systems in the chiral limit at relatively weak couplings. In Ref. [137], we established the existence of a novel phase with unusual properties. In particular, we showed that the single-site shift symmetry ("S^4") of staggered fermions is spontaneously broken ("$\not{S}^4$") in this phase. The single-site shift symmetry is an exact symmetry of the staggered lattice action (even at finite fermion mass); it ensures that the chiral condensate measured on even lattice sites is identical to that measured on odd sites, and the underlying gauge configurations exhibit the usual discrete translational symmetry. The breaking of this symmetry has never been observed before, and we suspect that the $\not{S}^4$ phase is a purely lattice phase with no continuum limit, like the parity-breaking Aoki phase of Wilson fermions.

Other groups exploring the 12-flavor system with different staggered actions have reported similar results, though to our knowledge they have not shown the breaking of the single-site shift symmetry. The general consistency of these results obtained with very different actions indicates that we are observing a robust feature of lattice gauge theories with many staggered fermions. We have also observed an $\not{S}^4$ phase in our studies of the 8-flavor system, but we found no evidence of it for $N_f = 4$. If the phase exists in 2+1-flavor lattice QCD it is most likely at very strong gauge coupling. We continue to explore this intriguing phase, and are particularly interested in its universality both with different actions and different numbers of fermions.

3.4 Finite temperature studies

The finite-temperature phase structure of IR-conformal systems is very different than that of confining and chirally broken theories. In the latter case, a finite-temperature phase transition separates chirally broken and chirally symmetric phases in the massless limit. On the lattice, the location of the transition approaches $\beta_F^{(c)} \to \infty$ as the temporal extent of the lattice $N_t \to \infty$. This transition is expected to be first order if $N_f \geq 3$. On the other hand, zero-temperature IR-conformal systems are chirally symmetric in the massless limit, and therefore have no finite-temperature transition in the continuum. Any transitions observed in finite-temperature lattices studies of IR-conformal systems must therefore converge to a strong-coupling bulk (zero-temperature) transition, with $\beta_F^{(c)}$ constant as $N_t \to \infty$. In this way, the N_t-scaling of finite-temperature phase transitions in the chiral limit can distinguish IR-conformal and confining systems.

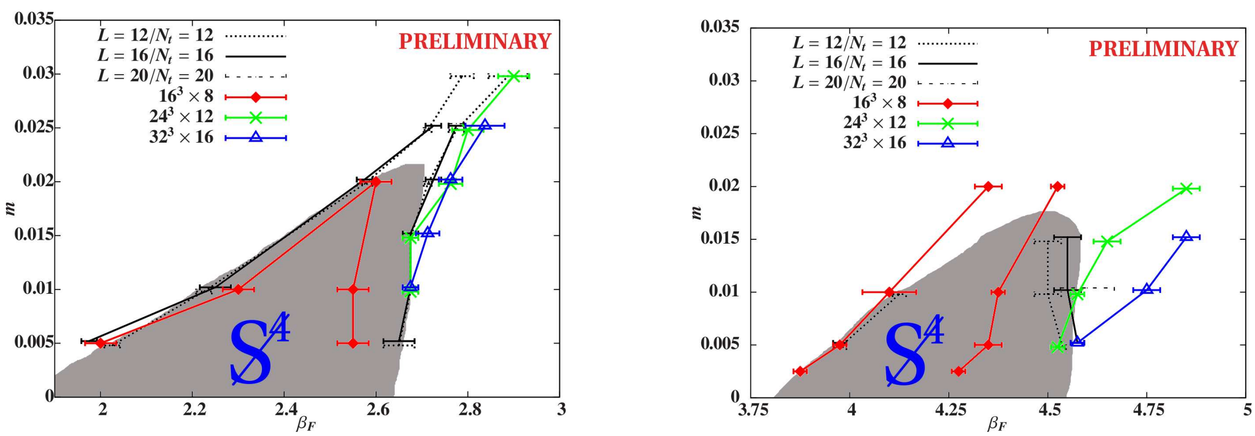

Figure 2.5: Bulk and finite-temperature transitions in the β_F–m plane on several lattice volumes with $N_f = 12$ (left) and 8 (right), from Ref. [143]. The $\not{S}^4$ phase is indicated by shaded regions bordered by black lines (including preliminary $40^3 \times 20$ results). The colored points indicate finite-temperature transitions; for $N_f = 12$ these accumulate at the bulk transitions surrounding the $\not{S}^4$ phase, while for $N_f = 8$ they can move to weaker couplings as N_t increases.

Fig. 2.5 presents an interesting contrast between the 12- and 8-flavor systems. For $N_f = 12$ (left), the finite-temperature transitions get stuck at the bulk transition on the weak coupling side of the $\not{S}^4$ phase, behavior that is consistent with an IR-conformal weak-coupling phase. In the 8-flavor system (right), the finite-temperature transitions can pass through the bulk transition, and move to larger $\beta_F^{(c)}$ as N_t increases. However, for our lightest fermion mass $m = 0.005$, the 8-flavor $N_t = 16$ transition is surprisingly close to the $N_t = 12$ transition. We conjecture that this is due to the influence of the nearby $\not{S}^4$ phase, and are generating $40^3 \times 20$ lattices to clarify this situation. Even though our results from several complementary studies indicate that the 8-flavor system is chirally broken, this strange behavior at $m = 0.005$ is a reminder that we need to be careful when working with such strong couplings.

3.5 Study of the Dirac eigenvalue spectrum

We are also studying the eigenvalue spectrum of the massless staggered Dirac operator, which we have found to be an extremely powerful observable containing a wealth of information. The eigenvalue spectral density $\rho(\lambda)$ distinguishes between the $\not{S}^4$ phase, chirally symmetric systems, and chirally broken systems, supplementing the other observables discussed in the previous two sections. In addition, when the eigenvalue distribution of a chirally broken system is compared to random matrix theory, it predicts the chiral condensate Σ. While there is no comparable prediction for IR-conformal systems, in this case the eigenvalues can be used to predict the mass anomalous dimension γ_m that governs the infrared dynamics of the system.

In Ref. [137] we used the scaling of the lowest-lying eigenvalues on different lattice volumes to obtain a preliminary prediction for the mass anomalous dimension of the 12-flavor theory. To improve upon that result, we recently turned our attention to the mode number, the integral of the spectral density. Ref. [144] showed that the mode number is renormalization group invariant, and used it to determine the chiral condensate of QCD. More recently, Ref. [145] used the mode number to predict γ_m for SU(2) gauge theory with two adjoint fermions, a system generally believed to be IR conformal.

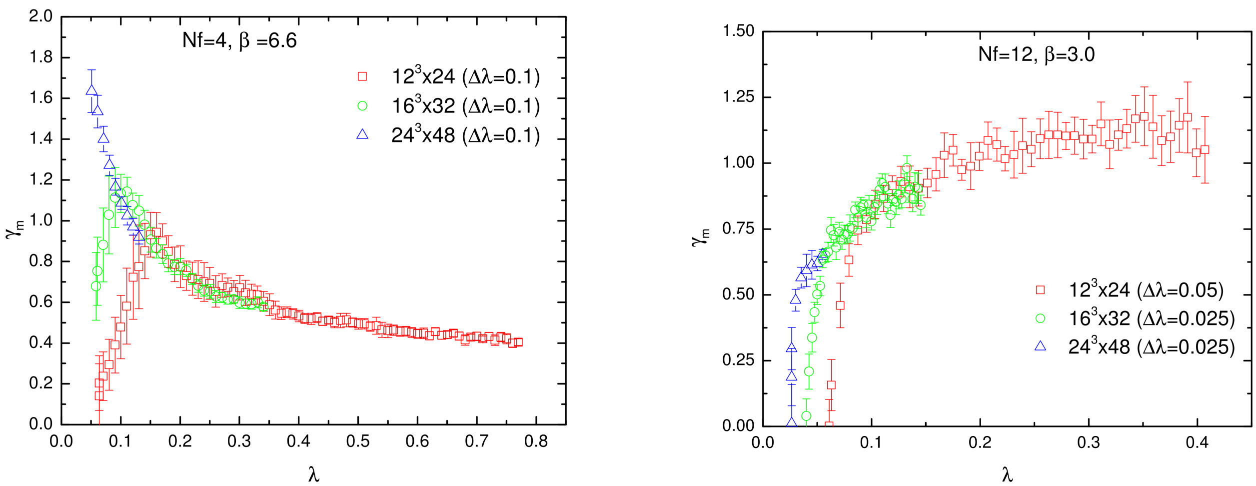

Figure 2.6: The anomalous dimension γ_m as a function of λ, on volumes $12^3 \times 24$ (red squares), $16^3 \times 32$ (green circles) and $24^3 \times 48$ (blue triangles). Left panel: 4-flavor system at $\beta_F = 6.6$ and $am = 0.0025$. Right panel: 12-flavor system at $\beta_F = 3.0$ and $am = 0.0025$. Both plots are from Ref. [146].

However, there is a complication that Ref. [145] did not consider: since the eigenvalue λ is a dimensionful quantity, the anomalous dimension $\gamma_m(\lambda)$ is energy-dependent. Since we have good data at many different volumes with small fermion masses, we can explore this energy dependence by fitting the mode number over small ranges $\Delta\lambda$. Fig. 2.6 presents some results for the 4- and 12-flavor systems, which we recently published in Ref. [146]. Apart from finite-volume effects for small λ, $\gamma_m(\lambda)$ for $N_f = 4$ decreases steadily as λ increases towards the ultraviolet. This is the qualitative energy dependence expected from perturbation theory. By contrast, $\gamma_m(\lambda)$ increases with λ in the $N_f = 12$ system at the relatively strong bare coupling $\beta_F = 3.0$, indicating backward flow and the presence of an infrared fixed point. Our $N_f = 12$ data at weaker gauge couplings (not shown in Fig. 2.6) are consistent with this interpretation. By combining results from several volumes and bare couplings we obtain the preliminary prediction $\gamma_m^* = 0.27(3)$ for the universal mass anomalous dimension at the IR fixed point.

These investigations of the Dirac eigenvalue spectrum form the core of Anqi Cheng's PhD research.

4 Research of K. T. Mahanthappa

During the past three years my research has focused on family symmetries based on finite groups combined with supersymmetric grand unification models. The main aim is to reduce the number of parameters in the Yukawa sector for both quarks and leptons. In particular, an SU(5) grand unified model combined with the family group T' is used. I also have been investigating leptogenesis and lepton flavor violation in SUSY GUT models with family symmetries that give rise to tri-bimaximal neutrino mixing with corrections. Mu-Chun Chen of the University of California at Irvine has been my collaborator.

Finite Group T' as the Family Symmetry and a Geometrical Origin of CP Violation. The global fit of various neutrino oscillation experiments indicates that the neutrino mixing matrix is close to the tri-bimaximal mixing pattern. The predictions of the tri-bimaximal mixing pattern for θ_{23} and θ_{13} agree with the experimental best fit values, $\sin^2 2\theta_{23} = 1$ and $\sin\theta_{13} = 0$, and it gives a prediction for the solar mixing angle $\tan^2\theta_{12} = 1/2$ consistent with the best fit value $\tan^2\theta_{12} = 0.43$ from the global fit. Even though the tri-bimaximal mixing pattern can arise naturally from the group theoretical CG coefficients of an underlying A_4 symmetry [156] in the lepton sector, there is nevertheless no CKM mixing when the A_4 symmetry is generalized to the quark sector. The group T' [157], which is the double covering group of A_4, has all the group theoretical properties of A_4, and thus it allows the tri-bimaximal mixing pattern to arise in the neutrino sector. In addition, it has three inequivalent irreducible doublet representations that do not exist in A_4. This enables the $2+1$ quantum number assignment in the quark sector, which has been shown to give realistic quark masses and mixing angles as in the case of $SU(2)$ family symmetry [158].

In [159] we have proposed an SU(5) grand unified model combined with the group T', which successfully gives rise to tri-bimaximal leptonic mixing as well as realistic CKM matrix elements for the quarks. Due to the existence of the complex CG coefficients in T', we pointed out in [160], for the first time, that CP violation in the quark and lepton sectors can be entirely geometrical in origin. Only nine operators are allowed in our model due to the presence of an additional $Z_{12} \times Z'_{12}$ symmetry. Our model is hence very predictive, the total number of parameters being nine in the Yukawa sector for all 22 observable masses, mixing angles and CP phases for quarks and leptons. In addition, our model provides a dynamical origin for the mass hierarchy. The Georgi-Jarlskog relations for three generations are accommodated in our model; this inevitably requires non-vanishing mixing in the charged lepton sector, leading to corrections to the tri-bimaximal mixing pattern. These corrections are predicted in terms of the Cabibbo angle and the group theoretical factors of T' and $SU(5)$ only. Our model predicts, $\tan^2\theta_\odot \simeq \tan^2\theta_{\odot,\text{TBM}} + \frac{1}{2}\theta_c \cos\delta_\ell$, which is a consequence of the Georgi-Jarlskog relations in the quark sector, with δ_ℓ being the leptonic Dirac CP phase. The correction accounts for the difference between the experimental best fit value and the tri-bimaximal mixing prediction for the solar mixing angle. Given that $\Delta m^2_\odot > 0$, our model predicts a normal hierarchy for the atmospheric neutrinos $\Delta m^2_{\text{atm}} > 0$.

In the neutrino sector, since only the vector representations are involved, all CG coefficients are real. However, because the first two generations of the $SU(5)$ 10-dimensional representations form a doublet (spinorial) representation of T', the CG coefficients can be complex, leading to complex mass matrices for the up-type quarks, down-type quarks and thus the charged leptons [160]. These therefore give rise to explicit CP violation in both the quark and lepton sectors. In the quark sector, our predictions for all CP violating measures are consistent with current experimental values. In particular, we have the prediction for the unitarity triangle with $\gamma \simeq 45^o$. From the complex CG coefficients in the charged lepton mass matrix, our prediction for the leptonic Dirac CP phase is $\delta_\ell \sim 227^o$, which is very close to the current best fit value from SuperK of 220^o [161]. The model also predicts non-vanishing θ_{13}, which is related to the Cabibbo angle as $\theta_{13} \sim \theta_c/3\sqrt{2} \sim 0.058$. This value is on the low side compared to the recent results from Daya Bay and RENO. Recently we have been able modify our model to obtain agreement with experiment; this leads to small corrections to other mixing angles but keeps the same values for the CP violating phases.

During 2009-2012, this work was presented in plenary talks and invited talks by my collaborator Mu-Chun Chen and myself, the latest being at the 6th International Workshop on Low Energy Neutrinos (Seoul, South Korea, November 9 - 12, 2011), Intensity Frontier Workshop (Rockville, MD, November 30 - December 2, 2011) and Symposium on Dark Matter and Neutrinos (Bengaluru, India, August 16 - 17, 2011). The modified model was the subject of invited talk at the international Workshop on Neutrino Masses and Mixing Angles (Trieste, Italy, 17 - 21, September, 2012, and also at Snowmass on the Pacific: KITP Conference (May 29 - 31, 2013) by K.T. Mahanthappa. It was also the subject of several invited seminars and colloquia.

Leptogenesis. It has been pointed out [162] that leptogenesis in models that give tri-bimaximal neutrino mixing from a finite group family symmetry such as A_4 predict a vanishing lepton number asymmetry even when flavor effects are included. In [163] we found the general necessary conditions for non-vanishing leptogenesis. These conditions are not satisfied in most models based on A_4 utilizing the usual seesaw realization for tri-bimaximal neutrino mixing.

In [163], we generalize our $SU(5) \times T'$ model [159],[160] to be supersymmetric and we propose an alternative seesaw realization for the neutrino sector, which satisfies the necessary conditions for non-vanishing leptogenesis. In the alternative seesaw realization, as the right-handed neutrinos form a triplet under T', the right-handed neutrino Majorana mass matrix is real. Consequently, leptogenesis in our model depends only on the low energy leptonic CP phases, the Dirac phase as well as the two Majorana phases. This leads to a strong correlation between CP violation in leptogenesis and in neutrino oscillation. We have found that the radiatively generated right-handed neutrino mass splitting gives rise to a non-zero asymmetry through resonant leptogenesis in the presence of the flavor effect. The lepton number asymmetry in our model is predicted to be $\sim 10^{-6}$, which is the right amount to explain the observed matter asymmetry in the universe.

During 2011-2012, this work has been presented at an invited talk at the Workshop on Theoretical Issues in Neutrino Physics (Korean Institute of Advanced Study, Seoul, South Korea, November 13 - 16, 2011).

Vacuum Alignment and Implications for Flavor Structure in Soft SUSY Sector. Currently we are constructing the superpotential that gives rise to the symmetry breaking patterns associated with the fermion mass generation. As it turns out, vacuum alignment can be achieved in a simpler way in the supersymmetric case in the presence of the driving fields which have linear couplings with the flavon fields in the model. In addition, we include the soft SUSY breaking sector, which is also determined by the T' family symmetry. We are investigating the capability of the T' symmetry in solving the SUSY flavor and CP problems.

Family Symmetry based on T' in Extra Dimensions. In addition to solving the gauge hierarchy problem, the Randall-Sundrum (RS) model also provides a new way to generate the fermion mass hierarchy and mixing by localizing fermions at different locations along the fifth dimension. Due to the presence of the 5D bulk mass terms which generically are non-universal, however, flavor-changing neutral currents (FCNCs) can arise at the tree level, leading to strong constraint on the first KK mass scale. By assuming minimal flavor violation [157], it is possible to relax the bound on the first KK mass scale to be as low as (2-3) TeV. The alignments proposed in [162], nevertheless, are purely phenomenological. Furthermore, fine-tuning is still required in these models in order to simultaneously accommodate both large neutrino mixing and their mass hierarchy, as in general RS models.

In [164], we have proposed an alternative in which the tree-level FCNCs are absent due to the T' family symmetry. The group A_4 has been utilized as a family symmetry in RS [165]. Nevertheless, it does not address the quark sector where the constraints on flavor violation are more stringent, especially those involving the first two families. As we have shown in [159], [160], the T' family symmetry can give rise to tri-bimaximal neutrino mixing and realistic CKM mixing matrix as well as CP violation from the CG coefficients. This thus alleviates the fine-tuning present in generic RS models required by having a realistic neutrino mass spectrum and mixing pattern. In our model, as the first two generations of quarks transform as doublets under the T' symmetry, the Z boson couples to the first generations universally since they have an identical bulk mass term. Similarly, in the lepton sector, as all three lepton doublets form a triplet of T', as required in order to get tri-bimaximal mixing, they have a common bulk mass term and thus universal Z couplings. All tree level FCNCs in the lepton sector and those that involve the first two generations in the quark sector are thus absent, allowing a low KK mass scale. We have found a set of 5D bulk masses that gives rise to realistic masses and mixing angles in both the quark and lepton sectors. We are now investigating the implications for FCNCs at one-loop as well as flavor violations mediated by the charged current interactions, which are not suppressed by the minimal flavor violation assumption.

Lepton Flavor Violation and Neutrinoless Double Beta Decay in the T' Model. In the framework of SUSY GUTs with mSUGRA boundary conditions at the GUT scale, the predictions for various lepton flavor violating processes are determined in terms of the Yukawa matrices and the five soft SUSY parameters. I have investigated [166], in collaboration with Chen, Meroni, and Petcov, the predictions for various lepton flavor violating processes in the SUSY $SU(5) \times T'$ model. Due to the mass sum rule in the model, we have found that the prediction for the neutrinoless double beta decay matrix element is ~ 0.0036 eV. In addition, we have the prediction of $\mathrm{Br}(\mu \to e\gamma) < \mathrm{Br}(\tau \to e\gamma) < \mathrm{Br}(\tau \to \mu\gamma)$.

Finite Group T' for Neutrino Mixing and Dark Matter. Most dark matter models stabilize the dark matter with a Z_2 symmetry, such as R-parity in the MSSM, KK parity in universal extra dimension models, or T-parity in little Higgs models. The general case of the Abelian symmetry Z_N to stabilize the dark matter has been discussed [167]. We are investigating the possibility of stabilizing the dark matter with the T' family symmetry. Due to the existence of non-trivial CG coefficients which are intrinsically complex, in addition to having unique signatures at the collider experiments, the dark matter co-annihilation cross section in the T' model can be very distinctive from those in models based on Z_N symmetries. We are also studying possible signatures of the complexity of the CG coefficients at the colliders, in particular the ratios of various decay branching fractions.

5 Research of S.P. de Alwis

5.1 Introduction

Much of my research over the last grant period has been directed towards refuting the often heard claim that string theory has no phenomenological predictions. In fact there are certain generic predictions of large classes of string theoretic models that are (or will be) testable. The approach has been based on the following observations.

- Supersymmetry is a necessary ingredient of string theory. However the theory does not naturally set the scale of supersymmetry breaking. Nevertheless given the existence of some indirect evidence for low scale supersymmetry breaking (such as gauge coupling unification, a natural candidate for dark matter, resolution of the hierarchy problem, a driving mechanism for electroweak symmetry breaking etc) it is reasonable to expect that the world is described by some solution (or class of solutions) to string theory which permit low scale (i.e. TeV scale) supersymmetry breaking.
- From a bottom up point of view there are many candidates for a theory of supersymmetry breaking. A theory of supersymmetry breaking must be a theory of local supersymmetry and its breaking, since broken global SUSY does not allow the fine tuning of the cosmological constant (CC) to zero. Hence such theories must take the form of a supergravity (SUGRA) that incorporates a supersymmetric version of the standard model (such as the MSSM) and realizes low energy supersymmetry breaking. Amongst the most popular such bottom up theories are a) minimal supergravity (mSUGRA) b) anomaly-mediated supersymmetry breaking (AMSB) and its variants and c) gauge mediated supersymmetry breaking (GMSB).
- From the above point of view it is hard to decide (besides subjecting them to experimental tests) which of these mechanisms is preferred. In mSUGRA for instance the entire construction is based on finding a simple parametrization of what might emerge at some high scale (such as the GUT scale) for SUSY breaking, and using the renormalization group to make statements about TeV scale physics.
- The top down approach is on the other hand more restrictive and hence more predictive. Here one begins with a class of string theoretic models for four dimensional (MSSM type) physics. An essential requirement is that the ground state solution of the string theory has all the moduli stabilized with the possibility of choosing internal fluxes such that the cosmological constant can be taken to be in the observed range. Given that such choices can affect the detailed phenomenology (Yukawa couplings etc) the only meaningful questions that can be answered are qualitative/semi-quantitative ones.
- Among these is the nature of SUSY breaking. In other words does string theory favor one or other of the phenomenologically motivated supersymmetry breaking mechanisms.
- Finally one might ask whether such a string theory based model for phenomenology can provide the framework for realizing a viable theory of inflationary cosmology. Are there specific predictions for cosmological parameters in such a model?

Summary of accomplishments

A coherent picture of string phenomenology based on type IIB string theory was achieved in [168]. The outcome of this investigation is an extremely simple phenomenology which is essentially dependent on two parameters, the gravitino mass and the ratio of the Higgs vacuum expectation values ($\tan\beta$). The SUSY breaking and mediation mechanism that emerges has been called "inoAMSB". Effectively this is a scenario in which at the GUT/string scale the soft supersymmetry breaking terms are highly suppressed (sequestered), except that the gaugino masses are effectively determined by the Weyl anomaly. Renormalization group running then gives electroweak symmetry breaking and the soft SUSY breaking phenomenology at the TeV scale. This is discussed in [169],[170] and [173]. In this last paper Givens and I pointed out that once one imposes all the constraints coming from standard cosmology, the lightest superpartnner (LSP) becomes a candidate for dark matter (saturating the observed dark matter density) and the Higgs mass is in the 122-125 GeV range. Furthermore the LSP is around 1.4 TeV in mass - perhaps it may just be possible to see it at the LHC! In any case this (and the rest of the spectrum of SUSY partners) is a clear prediction of this class of string theoretic models and is a significant achievement in string phenomenology.

Summary of Goals

A major goal of this line of investigation was to identify a class of models coming from string theory that not only satisfies all phenomenological and cosmological constraints (as in the previous paragraph) but also gives a natural candidate for inflation. Furthermore the constraints of thermodynamics on cosmological models emerging from string theory also need to be investigated further.

5.2 String Phenomenology - Large Volume Scenario models

The only viable string theory based derivation of a low energy SUGRA with supersymmetry breaking is at this point the so-called large volume scenario (LVS) for compactification of type IIB strings [174]. The main advantage of this scenario is that the (supersymmetric) standard model is situated on D3- or D7-branes so that it is effectively localized. Thus the moduli stabilization problem can be studied independently of the local physics on the brane.

inoAMSB from LVS

In the work discussed in [168] I showed that the mechanism for mediation that emerges from these string theory considerations, is to have gaugino masses arising from Weyl anomaly effects, while the scalar masses are generated by renormalization group running. The classical masses in this scenario are suppressed since it was shown in this paper that there is a lower bound on the volume of the internal space due to the need to suppress flavor violating effects so that we have a sequestered situation where the quantum effects determine the soft masses. This is the mechanism we called inoAMSB in [169]. As mentioned above the phenomenology that emerges is extremely simple in that it depends essentially only on two parameters - the gravitino mass and the ratio of the Higgs vacuum expectation values $\tan\beta$. The phenomenology of this class of string theoretic models has been investigated [169] [170] in collaboration with Howard Baer (University of Oklahoma), his students and postdocs, and my student Kevin Givens.

Single Kaehler modulus

In [168] I pointed out that in general LVS models would have unacceptable flavor changing neutral current interactions (FCNC), but it was also shown how to solve the problem by focusing on a subset of this class. Now since the origin of the problem was the fact that the LVS construction needed more than one Kaehler modulus, it seemed appropriate to understand whether it is possible to have a type IIB string theory construction with just one Kaehler modulus. Kevin Givens I have investigated such constructions analytically as well as numerically [171]. In the analytic work we found that it is possible to get compactifications which have SUSY breaking and a nearly zero and positive cosmological constant (CC), but it was not possible to get the SUSY breaking to be at the TeV scale. In the numerical investigation, minima which had low scale SUSY breaking (in addition to having a zero CC) were found, but these were rather special situations. The main conclusion of this investigation was that one really needs more than one Kaehler modulus to get a phenomenologically interesting class of models as in [168].

Constraints on LVS Compactifications of IIB String Theory

In this work [172] I have argued that once all theoretical and phenomenological constraints are imposed on the different versions of the Large Volume Scenario (LVS) compactifications of type IIB string theory, the one discussed above, namely inoAMSB, is favored. The only other theoretically (possibly) viable version gives a phenomenology in which cosmological constraints cannot be satisfied. It is also shown in this work that arguments questioning sequestering in LVS models are not relevant in this case. In another paper which I published at the end of last year [175] I show that LVS models that are based on moduli field redefinitions are based on assumptions that involve pushing low energy field theory arguments beyond the string scale (i.e. beyond their regime of validity). Hence such models cannot be derived in any meaningful sense from the underlying string theory. These two investigations essentially show that the only viable model coming from IIB LVS compactifications is that discussed in [168].

GMSB from string theory

GMSB naturally suppresses flavor changing neutral currents (FCNC) but is usually discussed within the global SUSY context. In line with the general program outlined earlier I investigated (in collaboration with Z. Lalak of Warsaw University) [176] the viability of GMSB within string theory. This requires (unless additional fine-tuning is used) that the lightest string theory modulus is heavy compared to the SUSY breaking scale of GMSB, so that they can be integrated out supersymmetrically. What was found is that while there is no insurmountable barrier to the existence of such models, they seem to be rather hard to come by within the string theory context.

5.3 General Issues in SUSY Breaking and Mediation

Unified treatment of SUSY Breaking

In [177] I gave a unified treatment of different models of supersymmetry breaking and mediation from a four dimensional effective field theory standpoint. One of the main results of this work was that, contrary to common belief, there is no particular advantage to GMSB compared to various gravity mediated versions of SUSY breaking scenarios, even for FCNC suppression. The difficulties of all these scenarios and their string theory embedding are also discussed.

Further work along these lines was done in [178]. In particular the assumptions made for AMSB and GMSB are discussed. In fact I showed that the former (including the expressions for the slepton and squark masses), can be derived without introducing the so-called Weyl compensators. This argument shows that the essential input for the derivation of these formulas is a certain factorization assumption. This also clarifies why these formulas are not valid in general (since this assumption is quite a strong one), even in the so-called sequestered situation where the classical contribution to the soft masses is negligible. In contrast, the assumption that goes into GMSB is simply that the gravitino mass is well below the soft mass scale, and then these general formulas give the relevant GMSB formulas. The assumptions that go into the other main SUSY breaking mechanisms are also clarified in this treatment.

In [179], which is a further elaboration of my earlier work [180], a detailed discussion of the arguments for the gaugino mass in AMSB is given, and it is pointed out that they necessarily imply explicit breaking of local supersymmetry. As explained in detail in this work the problem is a misidentification of the scalar compensator with the density compensator of supergravity. The point is that the Einstein frame expression for the complete SUGRA coupled to a gauge theory and chiral superfields, is obtained from the off-shell conformal frame formulation with auxiliary fields, only after a field redefinition effected by a Weyl transformation generated by a chiral scalar superfield. The latter is exactly what was used, for instance in the standard text book by Wess and Bagger. In the quantum theory theory however, since the path integral measure is not invariant under these redefinitions, as a result of the transformations the gauge coupling (superfield) acquires a term proportional to the chiral superfield that effects the transformation. Once the latter is expressed in terms of the original dynamical chiral superfields of the theory one gets additional terms for the gaugino mass. However all of these will be proportional to the F-terms of physical fields, and therefore (as is the case with the classical term) the gaugino mass will vanish when these terms are zero.

Local perspectives on global issues

Regardless of whether or not GMSB is embedded within string theory it is necessarily embedded within SUGRA. The main reason for this is that within global SUSY there is no way to cancel the cosmological constant (CC) which is generated after SUSY breaking - a CC which is necessarily at the SUSY breaking scale - i.e. many orders of magnitude above the observed scale. In GMSB model building, this aspect is generally ignored, or is addressed after the main consequences of the model are worked out. The contention of work that was published at the end of last year [182] is that there are several arguments that are made in the literature on GMSB and the associated SUSY breaking models, that need to be revised in the light of SUGRA. In particular in this paper the different limits that are possible in going from SUGRA to global SUSY are discussed. Of particular relevance to this investigation are the bounds on value of the superpotential and issues connected with so-called Fayet-Illiopoulos (FI) terms in global and local supersymmetry

Moduli in AdS supergravity

I'm investigating with Jan Loius (Hamburg/DESY), Liam McAlister (Cornell) and Alexander Westphal (DESY), some issues regarding the existence of moduli spaces in supergravity in Anti-deSitter space. While this may be of relevance to the AdS/CFT conjecture, it is certainly of intrinsic interest in supergravity. What appears confusing is the fact that in AdS supersymmetry there are massless multiplets (with the complex scalar being massless) but on the other hand from an examination of the supergravity potential it appears that (generically) no moduli are present. The work is aimed at clarifying this issue - in particular we find many examples in which there are massless axions/Goldstone bosons. Furthermore we can show that there are no complex moduli. It appears that the resolution of the apparent paradox is that the definition of what is massless in terms of the group theory (Wigner type) analysis is not (in AdS space) the same as what constitutes a modulus (in the sense of being a flat direction in the potential). We are in the process of analyzing various ramifications of these observations.

SUSY breaking vacua of heterotic strings

This is work that I've done in collaboration with Michele Cicoli and Alexander Westphal [183]. As discussed above, currently the best studied case of moduli stabilization with SUSY breaking is type IIB. Unfortunately so far it has not been possible to realize the standard model (without chiral exotics) in this context, though much progress has been made recently. In the case of the heterotic string on the other hand there are many examples where the standard model is explicitly realized (though with additional $U(1)$ gauge groups). Nevertheless up to now the problem of stabilizing moduli in a SUSY breaking minimum has not been solved. In our paper we have shown how to stabilize all the moduli and the dilaton using a combination of fluxes, non-perturbative gaugino condensate terms and world sheet instanton terms. The upshot is that generically compactification of the heterotic string leads to high (GUT) scale supersymmetry breaking. Furthermore the ability to tune the cosmological constant is also severely restricted.

6 Research of Oliver DeWolfe

In the past three years, my research has focused on using the gauge/gravity correspondence to make contact between string theory geometries and strongly coupled quantum field theories with potential relevance to laboratory physics. The primary projects in this area I will describe are a study of fermionic behavior and Fermi surfaces in $\mathcal{N} = 4$ Super-Yang-Mills theory, and a holographic model of the phase diagram of QCD. Outside the field of gauge/gravity duality, I will also describe two works related to the role of string theory as a theory of quantum gravity, one discussing anomalies in ten-dimensional supergravity theories, and the other the brane resolution of geometries with closed timelike curves. Finally I describe a recently completed review of the connection between string theory and heavy ion physics.

During this time I have graduated two PhD students, both of whom were heavily involved with these projects. Charles Max Brown graduated in Spring 2010 and is currently an assistant professor of physics at Kentucky State University; Christopher Rosen defended his dissertation in Spring 2012 and is now a postdoc at the Crete Center for Theoretical Physics at the University of Crete with Elias Kiritsis. I have begun working with a new student, Oscar Henriksson.

6.1 Fermi surfaces in $\mathcal{N} = 4$ Super-Yang-Mills theory

The gauge/gravity correspondence, or AdS/CFT correspondence, is a duality between non-gravitational quantum field theories and gravitating systems in higher-dimensional curved space, characterized as "holographic" for the way the gravity system, like a hologram, is generated from a set of lower-dimensional data. Beyond the fundamental implications for the nature of spacetime and the character of quantum gravity, the gauge/gravity correspondence has proven extremely useful for the way it relates strongly-coupled quantum field theories to weakly curved geometries with suppressed string corrections; precisely in the regime where the field theory is intractable to most methods due to the strong coupling, the gravity dual becomes easy to work with. Thus the gauge/gravity correspondence has provided entirely new theoretical tools for understanding strongly-coupled phenomena. Field theory systems at finite temperature are mapped to black hole geometries, and a great deal of information about correlation functions, operator dimensions, and transport coefficients can be obtained.

While the response of these systems to bosonic fluctuations is quite well-studied, the fermionic case is less so. Studying fermion fluctuations in charged black hole backgrounds at finite density can reveal the existence of Fermi surfaces and the spectrum of excitations around them in the field theory duals, providing a picture of the degrees of freedom and the phase structure of the quantum field theories. Such systems have been studied [184, 185, 186, 187] and tend to be so-called non-Fermi liquids, where a Fermi surface is present but no stable quasiparticle excitations around it exist. Such behavior is reminiscent of "strange metals" observed in high-temperature cuprate superconductors and heavy fermion systems, and any theory that could increase control of these fascinating systems would be welcome.

The past work in this direction has largely been "bottom-up," meaning the gravity systems do not descend from a known string theory or supergravity solution, but instead solve effective Lagrangians whose forms are chosen for convenience. Such methods are very useful (I will describe my own use of such techniques shortly) but they have two substantial drawbacks. First, the precise map between a quantum field theory and its gravity dual is only known for the cases that go through string theory, so while Fermi surfaces with non-Fermi liquid behavior in effective gravity set-ups have been found, it has not been possible to state what the dual quantum field theory is. Second, since the gauge/gravity correspondence finds its fullest justification in string theory, one may wonder whether any results found in a bottom-up approach not known to descend from string theory are only a consequence of parameters chosen in the effective Lagrangian that may be secretly unphysical.

$\mathcal{N}=4$ Super-Yang-Mills theory is dual to type IIB string theory in an anti-de Sitter spacetime; this is the most well-studied example of the gauge/gravity correspondence by far. $\mathcal{N}=4$ Super-Yang-Mills is a non-Abelian gauge theory, and in the limit of a large number of colors with strong coupling, the dual description reduces to type IIB supergravity. Studying the fermionic response of this theory at finite density is a natural thing to do, but had not been attempted, presumably due to the complexities of the fermionic part of the full supergravity action.

In [188] I studied this system, with my graduate student Chris Rosen and collaborator Steve Gubser from Princeton, and found a Fermi surface in strongly-coupled $\mathcal{N}=4$ Super-Yang-Mills at finite density; this work appeared in Physical Review Letters. Similarly to the "bottom-up" approaches, the solution acted as a non-Fermi liquid with no stable quasiparticles. There were, however, relatively long-lived resonances whose widths were parametrically smaller than their energies. The excitations also showed an unusual sixth-power dispersion relation. Thus we showed for the first time that holographic non-Fermi liquid states are not merely artifacts that exist only in an unknown, potentially pathological dual theory, but instead are present in the well-defined theory of $\mathcal{N}=4$ Super-Yang-Mills. In addition to the $\mathcal{N}=4$ SYM case, we also studied fermions in the gravity dual of the maximally supersymmetric three-dimensional ABJM theory, and found similar Fermi surface behavior there as well. Given the "top-down" nature of the construction, it was possible to begin an analysis of the state in the dual quantum field theory. The scaling of the Green's function suggests it is an adjoint fermion that forms the Fermi surface, and a simple Luttinger-style count suggests these gauginos carry most of the charge of the system.

In the work just described, a single fermionic mode was studied, in a relatively simple charged black hole background corresponding to the three possible chemical potentials of the theory being set equal to one another, establishing the existence of a top-down holographic Fermi surface. It is natural, however, to wish to go beyond a single case to study a wide variety of fermionic modes, in a variety of backgrounds with varying chemical potential, and attempt to classify the diversity of Fermi surface behavior. In [189], I investigated (again with Gubser and Rosen) the one-parameter family of black hole geometries where two chemical potentials of $\mathcal{N} = 4$ Super-Yang-Mills are the same but the third is different. Moreover, in this wide class of backgrounds, every spin-1/2 supergravity fluctuation not mixing with the gravitino fields was studied. Different modes display two, one or zero Fermi surface singularities, and dispersion relations and widths of excitations were obtained across the entire zoo. Two limits stood out as particularly interesting. In both of these limits, the entropy at zero temperature is vanishing; the nonzero entropy in the simpler models has been a source of confusion in the interpretation of the phase of the system in which the Fermi surface lives, and studying a case where such a zero-temperature entropy vanishes is of natural interest. In one case, a Fermi surface approaches the limit of a marginal Fermi liquid, which has been postulated to describe the optimally doped cuprates [191]; this limit is controlled by a supersymmetric solution and results could be derived analytically, including a hard gap in the conductivity. In the other, the so-called "2-charge" black hole, a soft gap in the conductivity accompanied Fermi surface singularities that did not show excitations with ordinary infalling boundary conditions; more research into this case is currently ongoing. Overall, I have demonstrated that $\mathcal{N} = 4$ Super-Yang-Mills theory displays a wide variety of non-Fermi and marginal Fermi liquid behaviors at finite density and strong coupling.

6.2 Holographic Phase Diagram of QCD

Another interesting strongly coupled field theory, of course, is quantum chromodynamics (QCD), the theory of the strong nuclear force. QCD at zero temperature is understood as a system of hadrons. As the temperature is increased, however, SU(3) gauge theory with 2 light quarks and a strange quark is expected to undergo a transition to a state of liberated quarks and gluons. Such phases of matter can be explored in heavy ion collisions. From lattice calculations, this is expected to be a rapid crossover, not a true phase transition. It is generally believed, however, that when one turns on nonzero chemical potential for baryon number, the crossover sharpens into a line of first-order phase transitions ending at a critical point (see *e.g.* [192]). Experimental exploration of this critical point is possible in the coming decade.

Lattice methods encounter difficulty at finite chemical potential, due to technical complication s in evaluating the path integral, referred to as the sign problem. Hence, other theoretical methods are naturally of interest. At the energies explored in heavy ion collisions at RHIC and LHC, the resulting quark-gluon plasma appears to be a strongly coupled fluid, and the gauge/gravity correspondence has already provided an explanation for the observed very small ratio of shear viscosity to entropy density [193, 194, 195]. As the critical point of QCD is of theoretical interest as well as potentially being observable in future heavy ion collisions, it is natural to use the gauge/gravity correspondence to study it.

Again with Gubser and Rosen, I generated a large set of numerical black holes whose thermodynamic properties match the phase diagram of QCD [196]. Since a useful gravity dual of QCD itself is not known, here we used bottom-up models where we chose the gravity dynamics to match the known thermodynamics of QCD as calculated with lattice methods at zero chemical potential. Thus we are taking the large-N limit of a gauge theory with the zero-density thermodynamics held fixed to match that of QCD. Adding a chemical potential then simply corresponds to adding electric charge to the black holes, and we used the effective action constrained by the QCD input to populate the phase diagram.

In confirmation of expectations, we found the crossover indeed sharpens into a line of first-order phase transitions at finite chemical potential. This first order line terminates on a critical point, whose critical exponents we were able to study; the resulting exponents satisfy nontrivial scaling relations and are consistent with mean field behavior. This is the first phase diagram of a QCD-like theory generated by holographic means and is a lovely confirmation of how the gauge/gravity correspondence realizes all the intricacies of strongly coupled field theories, in this case their phase structure, in black hole geometries. Furthermore, transport coefficients such as conductivity and viscosity are important if one wants to understand how a real system like a heavy ion collision would approach the critical point, and these we calculated from fluctuations around the black hole systems [197]. We found that convective transport is suppressed relative to previous expectations. A potential explanation is that the large N limit, which suppresses quantum corrections on the gravity side, also suppresses deviations from mean field behavior as well as convective transport.

6.3 Supergravity anomalies and brane resolution of closed timelike curves

While my research has largely focused on the gauge/gravity correspondence, I have also pursued a few projects involving the consistency of quantum gravity and its relation to string theory.

One involves anomalies in supergravity and the so-called "swampland". String theory has a huge number of vacuum solutions, called the "landscape"; yet not all possible low-energy quantum field theories emerge from string theory. The question is whether the theories that do not result from string theory are somehow inconsistent. The "swampland" [203] is the (possibly empty) set of quantum field theories coupled to gravity in a consistent fashion that cannot arise from string theory. Understanding the swampland is of natural interest: if it is not empty, and our universe lies in it, then string theory predictions can be falsified; if it is empty, string theory acquires the status of a universal quantum gravitational completion. A simple example (albeit far from phenomenology) is the situation for ten-dimensional supersymmetric theories. Anomalies rule out almost all possible gauge groups: only the famous string theory gauge groups $SO(32)$ and $E_8 \times E_8$, as well as two funny groups with abelian factors, $E_8 \times U(1)^{248}$ and $U(1)^{496}$, were believed to be consistent [204]. The latter two, with no realization in string theory, were natural candidates for the swampland; their existence seemed rather surprising. Recently, with Allan Adams and Washington Taylor (both MIT), I showed these theories to be impossible after all, as supersymmetry makes anomaly cancelation incompatible with abelian gauge invariance [205]; this work was also published in Physical Review Letters. Thus the ten-dimensional swampland is empty after all.

Another natural question about quantum gravity is whether and how quantum effects mitigate or remove pathologies in general relativity. Singularities are the most well-studied, and string theory indeed removes singularities in some (but not all) cases. Another interesting class of troublesome phenomena is that of closed timelike curves (CTCs). The pathology is nonlocal: each point may be well-behaved with weak curvature (and in string theory, small string coupling), and yet the global structure implies a breakdown in unitary evolution. Building on earlier work [202] (see also [199, 200, 201]) concerning a class of so-called Schrödinger black hole geometries, interesting because their isometry group matches the non-relativistic conformal symmetry of ultracold gases at unitarity [198], my student Max Brown and I noticed that the map that generates this class of geometries carries rotating black holes to spacetimes with closed timelike curves. We made a detailed study of the simplest case, and found that while the symmetry group is consistent with providing a gravity dual for the same non-relativistic conformal field theory defined on a sphere, the presence of CTCs made the geometry reminiscent of Gödel spacetimes, and so we dubbed it the Gödel-Schrödinger geometry [206]. We showed that analogously to other Gödel-type spacetimes [207, 208], there are signs that string theory indeed removes the pathology of the closed timelike curves: an observer's holographic preferred screen is too small to encompass an entire CTC, implying a holographic description may escape the violation of unitarity, while D3-brane probes become unstable precisely at the CTC radius, suggesting the condensation of branes will lead to an enhançon-type mechanism that modifies the space. This is suggestive that as with singularities, the quantum nature of gravity in string theory is aware of, and removes, the pathologies of closed timelike curves.

6.4 String theory and heavy ion physics review

During this time period I have also coauthored with Gubser, Rosen and Derek Teaney (Stony Brook) a review of the applications of the gauge/gravity correspondence to heavy ion physics [190]. This review focuses on current aspects of the correspondence that have not been emphasized as much as some others: non-equilibrium processes including generalizations of Bjorken flow, numerical simulations of black hole formation in asymptotically anti-de Sitter geometries, equilibration in the dual field theory, and hard probes, as well as equilibrium processes focused on transport coefficients, renormalization group running and the phase diagram. It is my hope that this review will be a useful contribution to the literature on the subject. This review was solicited by Progress in Particle and Nuclear Physics and was submitted in early 2013; it is currently under review by Prog. Part. Nucl. Phys.

6.5 Accomplishments

Of the research described above, I would select my major accomplishments as:

- The first study of Fermi surfaces and collective fermion behavior in $\mathcal{N} = 4$ Super-Yang-Mills theory, rather than in a bottom-up model or a defect model.
- The construction of the first holographic phase diagram of a gauge theory with QCD-like thermodynamics, and the detailed study of its critical point.
- The demonstration of the inconsistency of the ten-dimensional $E_8 \times U(1)^{248}$ and $U(1)^{496}$ $\mathcal{N} = 1$ supergravity theories, showing the ten-dimensional supersymmetric swampland is empty.

7 Theoretical Advanced Study Institute (Task T)

7.1 Introduction

The High Energy Theory Group of the University of Colorado at Boulder hosted the Theoretical Advanced Study Institute in Elementary Particle Physics (TASI) for four weeks in June during 2010 - 2012. It was supported by DoE under TASK T. (It was also supported by NSF (NSF Award #Phy-0753193; Title: Theoretical Advanced Study Institute in Particle Physics) during these years.)

K.T. Mahanthappa of University of Colorado at Boulder had been the general director of TASI since 1989 and Thomas DeGrand joined him as co-general director starting 2010. The national Scientific Advisory Board (SAB) of TASI consists of Sally Dawson, Chair (Brookhaven National Lab), M. Carena (FNAL), W. Carithers (LBL), C. Johnson (USC), G. Gemini (UCLA), T. Han (Pittsburgh), T. DeGrand and K.T. Mahanthappa. The local organizing committee consisted of S.P. (Shanta) de Alwis, Thomas DeGrand, Oliver deWolfe, Anna Hasenfartz and K.T. Mahanthappa.

The format and aims of three TASIs were similar to those of previous TASIs. The objective of TASI is to provide a series of lectures and seminars aimed at advanced graduate students on topics of current research in theoretical elementary particle physics and related experimental subjects, and thus broaden their horizon beyond the thesis topics they would be pursuing at their institutions. The atmosphere at TASI is such it brings about intense interaction among students and lecturers. Each summer TASI focuses on one or two broad topics in theoretical physics, topics chosen (by SAB and the general co-directors) being timely and relevant from both experimental and theoretical points of view. The active stalwarts in these topics are invited to direct the program in concert with the general co-directors.

By all accounts, these TASIs have been a great success. All Proceedings through TASI-11 with the exception of 2005 and 2007 have been published; the Proceedings of TASI-12 are in press. Since 2007 TASI has been video recorded and is available at its web site `http://physicslearning2.colorado.edu/tasi/tasi_2007.htm`.

7.2 TASI during 2010 - 2012

The themes and the outside program directors for the period were: (1) TASI 10: "String Theory and Its Applications: From meV to the Planck Scale," Michael Dine (UCSC), Thomas Banks (Rutgers/UCSC) and Subir Suchdev (Harvard); (2) TASI 11: "The Dark Secrets of Terascale," Konstantin Metchev (Florida) and Timothy Tait (UCI); (3) TASI 12: "Searching for New Physics at Small and Large Scales," Martin Schmaltz (Boston) and Elena Pierpaoli (UCSC). The number of selected students has been limited to 58/62 excluding those from our university; this number has been chosen by original SAB to be the optimum one to have interaction among the students, and students and lecturers. The number of lecturers (which included two or three experimentalists) each summer has ranged from 17 to 21, each lecturer usually giving three to five lectures (each lecture lasting 75 minutes with time for questions), and thus a mini course in his/her sub-field. In addition, student participants were encouraged to organize their own seminars (each lasting not more than 40 minutes) in free afternoons and evenings; these seminars, 20 to 30 of them every summer, brought the students closer together which led to more interaction and collaborations; this aspect of TASI has been very much valued by students as indicated by their comments long after they attended TASI. There were intense interactions between lecturers and students besides among students themselves. (The former is very much facilitated by encouraging the lecturers to stay in student housing where they sit together with students for meals; each summer about 50% of the lecturers have opted to stay in student housing.) I think that it is an understatement to say that TASI has been a huge success, and that it has become an important ingredient in training younger generations of particle theorists. Many of the alumni of previous TASIs are on the faculties of major research universities in the U.S. and abroad.

7.3 TASI- 2012 Program

For illustrative purpose we give details of TASI 12. . It was held during June 4 - 29, 2012. The topic chosen by SAB was "Searching for New Physics at Small and Large Scales." The program was organized by Professor Martin Schmaltz of Boston University and Professor Elena Pierpaoli of University of Southern California. Schmaltz is well known for his work on physics beyond the standard model, and Pierpaoli for her theoretical astrophysics contributions. As is obvious from the title of TASI 12 the topics covered by lecturers include both particle physics and cosmology and their interconnections. The lecturers and topics were:

Particle Physics:
Peter Skands (CERN): Introduction to QCD
Jesse Thaler (MIT): Super-tricks for Superspace
Michael Peskin (Stanford): Weak Interactions and Higgs, Theory
Yuri Gershtein (Rutgers): LHC and Higgs, Experiment
Veronica Sanz (York & CERN): Collider physics
Aaron Pierce (Michigan): SUSY at the LHC
Michele Papucci (Berkeley): SUSY Model Building
Jesse Shelton (Yale): Jet substructure and new physics
Rouven Essig (SUNY Stony Brook): Dark Matter from Particle Physics

Cosmology:
Edmund Bertschinger (MIT): Introduction to Cosmology
Robert Caldwell (Dartmouth): Dark Energy
Fabian Schmidt (Caltech): Modified gravity
Julien Lesgourgues (EPFL Lausanne & CERN): Cosmological Perturbations and Dark Matter
Leonardo Senatore (Stanford): Inflation
Shirley Ho (CMU & Berkeley): What Can We Learn from Large Scale Structure of the Universe?
Stefano Profumo (UC Santa Cruz): DM Constraints from Astrophysical Data

Public Lectures: (Since four years TASI has been having public lectures which have attracted large audiences.)
Robert Caldwell (Dartmouth): Einstein's Island and Invisible Cities of Cosmology
Michael Peskin (Stanford): The Higgs Boson: Is It Real?

Following the format of previous TASIs, there were two lectures of 75 minutes each during the morning, Monday through Friday. The afternoon format was less rigid, and included courses, individual seminars on selected topics, and discussion sessions. Typically, there were one or two lectures in the afternoon. There were student-organized seminars in the evenings. Weekends were left free for reading, informal discussions, and recreation. The schedule was organized so that introductory material was presented first, with advanced material and seminars on current research presented later. All participants attended the Institute for full duration as in the past TASIs.

7.4 Lecture-Note Volume and Video Recording

Since 1989, with the cooperation of the lecturers we have been able to bring out the lecture-note volume of each TASI usually by May - June of the following calendar year. The volumes have been useful to researchers in theoretical particle physics as they contain topics of current interest, and have been valuable to students all over the world because of the pedagogical presentation of advanced topics. Each volume is edited by external program directors. The volumes have been published by The World Scientific Publishing Company, Inc. (Singapore). The volumes for TASI 10 and TASI 11 have been published, and that of TASI 12 is in press.

7.5 Facilities and Dates

The Institute was held on the campus of the University of Colorado at Boulder, which is at a distance of 45 miles from the Denver International Airport. This beautiful campus is located in the foothills of the Rocky Mountains. There are excellent facilities for formal lectures, and seminar rooms for small discussion sessions. The lecture hall where the lectures are held is equipped with latest technology. These facilities were made available by the University free of cost. Also, computer labs were available to students and lecturers. The Physics Building Complex is wireless accessible. There are excellent facilities to house the lecturers and participants and provide meals.

The duration of the Institute was usual four weeks during June. TASI-12, June 4 - 29, 2012. The approximate cost of lodging and board in shared double was $1600.00 in the summer of 2012.

7.6 Comments on the Budget and Support from the University of Colorado

Most of the DoE budget was used to support the lecturers and some of the administrative expenses of TASI. Most of the NSF support is used to subsidize about 40% - 60% of the average expenses of each student and some of the administrative costs. The usual indirect costs, which is currently 52.5% of the direct costs, was waived by the University as has been done before. In addition, the University, through the Department of Physics, provided free building usage.

7.7 Broader of Impact of TASI

TASI is serving a very useful purpose of training next generations of theoretical high energy physicists to keep U.S.A. in the forefront of this research field in the world. As these trained personnel have a very versatile background in physics and mathematics including sophisticated computational techniques using computers, they have contributed and will continue to contribute in the task of keeping the country abreast in physical sciences and related fields.

As a service to the high energy physics community at large, starting with TASI 2007, videos of TASI lectures are made accessible at the TASI web site to anyone. This should be of great value to students and research workers all over the world.

Since 2008 TASI has sponsored public lectures for general audience by eminent persons on developments in high energy physics and cosmology.

Appendix 1

Publications and Talks

1 List of Colorado *BABAR* Publications and Talks

The following is a summary of *BABAR* publications and conference talks produced by our group in the last three years.

1.1 Publications

1. **Search for B-meson decays to $b_1\rho$ and b_1K^*** , B. Aubert *et al.* (*BABAR* Collaboration), *Phys. Rev. D* **80**(2009), 051101.
2. **B-meson decays to $\eta'\rho$, $\eta' f_0$, and $\eta' K^*$** , P. del Amo Sanchez *et al.* (*BABAR* Collaboration), *Phys. Rev. D* **82**(2010), 011502.
3. **Measurement of partial branching fractions of inclusive charmless B meson decays to K^+, K^0, and π^+**, P. del Amo Sanchez *et al.* (*BABAR* Collaboration), *Phys. Rev. D* **83**(2011), 031103.
4. **B^0 meson decays to ρ^0K^{*0}, f_0K^{*0}, and ρ^-K^{*+} , including higher K^* resonances**, J.P. Lees *et al.* (*BABAR* Collaboration), *Phys. Rev. D* **85**(2012), 072005.

1.2 Conference Talks

1. 5th Patras Workshop on Axions, WIMPs and WISPs (Durham, UK), A. Gaz plenary talk on light Higgs/Axion searches at *BABAR*, July 2009.
2. Lake Louise Winter School (Banff, Canada), A. Gaz parallel talk on CKM Angles and Sides, Feb. 2010.
3. ICHEP 2010 (Paris, France): A. Gaz, parallel talk on Charmless Hadronic B decays at *BABAR*, July 2010.
4. EPS 2011 (Grenoble, France): A. Gaz parallel talk on Recent *BABAR* measurements of hadronic B branching fractions, July 2011.
5. DARK 2012 (Frascati, Italy): A. Gaz, plenary talk on Search for dark photons and dark Higgs at *BABAR*, October 2012.

2 List of Colorado CMS Publications and Talks

The following is a summary of CMS publications and talks produced by our group between December 1, 2009 and April 30, 2013.

2.1 Publications

1. **Commissioning and Performance of the CMS Silicon Strip Tracker with Cosmic Ray Muons**, S. Chatrchyan *et al.* (CMS Collaboration), *JINST* **5**(2010), T03008.
2. **Commissioning and Performance of the CMS Pixel Tracker with Cosmic Ray Muons**, S. Chatrchyan *et al.* (CMS Collaboration), *JINST* **5**(2010), T03007.
3. **CMS Tracking Performance Results from early LHC Operation**, V. Khachatryan *et al.* (CMS Collaboration), *Eur. Phys. J. C* **70**(2010), 1165.
4. **Strange Particle Production in pp Collisions at $\sqrt{s} = 0.9$ and 7 TeV**, V. Khachatryan *et al.* (CMS Collaboration), *JHEP* **1105**(2011), 064.
5. **Search for Supersymmetry in pp Collisions at $\sqrt{s} = 7$ TeV in Events with Two Photons and Missing Transverse Energy**, S. Chatrchyan *et al.* (CMS Collaboration), *Phys. Rev. Lett.* **106**(2011), 211802.
6. **Measurement of the B^0 production cross section in pp Collisions at $\sqrt{s} = 7$ TeV**, S. Chatrchyan *et al.* (CMS Collaboration), *Phys. Rev. Lett.* **106**(2011), 252001.
7. **Search for Physics Beyond the Standard Model Using Multilepton Signatures in pp Collisions at $\sqrt{s} = 7$ TeV**, S. Chatrchyan *et al.* (CMS Collaboration), *Phys. Lett. B* **704**(2011), 411.
8. **Measurement of the Λ_b cross section and the $\overline{\Lambda}_b$ to Λ_b ratio with $J/\psi\Lambda$ decays in pp collisions at $\sqrt{s} = 7$ TeV**, S. Chatrchyan *et al.* (CMS Collaboration), *Phys. Lett. B* **B714**(2012), 136.
9. **Search for high mass resonances decaying into tau-lepton pairs in pp collisions at $\sqrt{s} = 7$ TeV**, S. Chatrchyan *et al.* (CMS Collaboration), *Phys. Lett. B* **B716**(2012), 82.
10. **Search for supersymmetry in events with b-quark jets and missing transverse energy in pp collisions at 7 TeV**, S. Chatrchyan *et al.* (CMS Collaboration), *Phys. Rev. D* **86**(2012), 072010.

2.2 Conference Talks

1. Lake Louise Winter School (Banff, Canada), K. A. Ulmer, parallel talk on the Performance of the CMS tracking detectors from the 2009 LHC run, Feb. 2010.
2. 22nd Rencontres de Blois (Blois, France), K. Stenson, parallel talk on Single and Double-Particle Studies at CMS, July 2010.
3. ICHEP 2010 (Paris, France), K. A. Ulmer, parallel talk on Measurements of Hadron Production at CMS, July 2010.
4. Joint Berkeley-MIT workshop (Cambridge, MA), B.R. Drell, plenary talk on Strange, Charm, and Beauty Production at CMS, Aug. 2010.
5. SUSY10 (Bonn, Germany), B. Heyburn, talk on Searches for SUSY in Di-photon Events, Aug. 2010.

6. 22nd Rencontres de Moriond (La Thuile, Italy), K. A. Ulmer, plenary talk on Heavy Flavor Production at CMS, March 2011.
7. 2011 APS meeting (Anaheim, CA), C. Edelmaier, parallel talk on Search for new physics in three or more lepton modes in pp collisions at $\sqrt{s} = 7$ TeV, April 2011.
8. CERN-Fermilab Hadron Collider Physics Summer School (CERN), K. Stenson, plenary lectures on tracking and particle identification, June 2011.
9. EPS 2011 (Grenoble, France): M.E. Dinardo, parallel talk on Measurements of b-quark production at 7 TeV with the CMS experiment, July 2011.
10. SUSY 2011 (Fermilab, Batavia, IL): K. A. Ulmer, plenary talk on Search for $B \to \mu^+\mu^-$ Decays at CMS, March 2012.
11. Joint Theory-Experiment Workshop on Searches for New Physics Via Heavy Quark Physics in Hadron Colliders (University of Washington, Seattle, WA): K. A. Ulmer, planary talk on Searches for New Physics in b Hadron Decays at CMS, May 2012.
12. Workshop on SUSY with 5 fb^{-1} at the LHC (Brookhaven National Laboratory, Upton, NY): K. A. Ulmer, plenary talk on sbottom and stop production at CMS, May 2012.
13. USCMS 2012 (Boulder, CO): K. A. Ulmer, plenary talk on 3rd Generation Supersymmetry Production at CMS, May 2012.
14. CIPANP 2012 (St. Petersburg, FL): E. Luiggi, parallel talk on Searches for new heavy resonances with CMS, June 2012.
15. ICHEP 2012 (Melbourne, Australia): K. A. Ulmer, parallel talk on Studies of rare beauty and charm decays with the CMS experiment, July 2012.
16. ICHEP 2012 (Melbourne, Australia): K. A. Ulmer, parallel talk on Studies of exotic charmonium and bottomonium states with the CMS experiment, July 2012.
17. PIXEL 2012 (Lake Inawashiro, Japan): A. Gaz, plenary talk on CMS Pixel Status, September 2012.
18. CHICAGO 2012 Workshop on LHC Physics in the Higgs Era (Chicago, IL): K. A. Ulmer, plenary talk on SUSY searches with heavy flavor from CMS and ATLAS, November 2012.
19. LHCP 2013 (Barcelona, Spain): A. Gaz, plenary talk on Searches for squarks and gluinos in events with missing transverse momentum, May 2013.

2.3 Seminar and Colloquium Talks

1. J. P. Cumalat, colloquium at Colorado State University, Ft. Collins, March 2010.
2. J. P. Cumalat, colloquium at Colorado State University, Pueblo, March 2011.
3. K. Stenson, colloquium at Vanderbilt University, April 2011.
4. K. Stenson, colloquium at University of Colorado, October 2011.
5. K. A. Ulmer, seminar at Fermilab, June 2012.
6. J. P. Cumalat, colloquium at Colorado School of Mines, September 2012.
7. K. A. Ulmer, colloquium at University of Denver, November 2012.
8. J. P. Cumalat, colloquium at Colorado State University, Pueblo, February 2013.

3 List of Colorado Neutrino Publications and Talks

The following is a summary of neutrino physics publications and talks produced by our group in the last three years.

3.1 Publications

1. **Event Excess in the MiniBooNE Search for $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ Oscillations**, A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), *Phys. Rev. Lett.* **105**(2010), 181801.
2. **Measurement of Neutrino-Induced Charged-Current Charged Pion Production Cross Sections on Mineral Oil at $E_{\nu} \sim 1$ GeV**, A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), *Phys. Rev. D* **83**(2011), 052007.
3. **Measurement of ν_{μ}-induced charged-current neutral pion production cross sections on mineral oil at $E_{\nu} \in 0.5 - 2.0$ GeV**, A. A. Aguilar-Arevalo *et al.* (MiniBooNE Collaboration), *Phys. Rev. D* **83**(2011), 052009.
4. **Precise Measurements of Direct CP Violation, CPT Symmetry, and Other Parameters in the Neutral Kaon System**, E. Abouzaid *et al.* (KTeV Collaboration), *Phys. Rev. D* **83**(2011), 092001.
5. **Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam**, K. Abe *et al.* (T2K Collaboration), *Phys. Rev. Lett.* **107**(2011), 041801.
6. **First Muon-Neutrino Disappearance Study with an Off-Axis Beam**, K. Abe *et al.* (T2K Collaboration), *Phys. Rev. D* **85**(2012), 031103.
7. **The T2K Experiment**, K. Abe *et al.* (T2K Collaboration) *Nucl. Inst. Meth.* **A659** (2011) 106.
8. **The T2K ND280 Off-Axis Pi-Zero Detector**, S. Assylbekov *et al.*, *Nucl. Inst. Meth.* **A686** (2012) 48.
9. **The T2K Neutrino Flux Prediction**, K. Abe *et al.* (T2K Collaboration), *Phys. Rev. D* **87**(2013), 012001.
10. S. Bhadra, M. Cadabeschi, P. de Perio, V. Galymov, M. Hartz, B. Kirby, A. Konaka and A. D. Marino *et al.*, "Optical Transition Radiation Monitor for the T2K Experiment," *Nucl. Instr.. Meth. A* **703**, 45 (2013).
11. K. Abe *et al.* (T2K Collaboration), "Measurement of the Inclusive NuMu Charged Current Cross Section on Carbon in the Near Detector of the T2K Experiment," *Phys. Rev. D* **87**, *092003 (2013).*

3.2 Conference Talks

1. Neutrino 2010 (Athens, Greece): M. M. Tzanov, review talk on resonance productions in neutrino interactions, June 2010.
2. ICHEP 2010 (Paris, France): E. D. Zimmerman, parallel talk on data from first T2K physics run, July 2010.
3. SLAC Summer Institute Topical Conference 2010: E. D. Zimmerman, plenary talk on recent MiniBooNE results, Aug. 2010.

4. 2nd International Neutrino Summer School (Tokai, Japan): E. D. Zimmerman, lecture on the physics of neutrino horns, Aug. 2010.
5. Neutrino Beams and Instrumentation Workshop 2010 (Tokai, Japan): A. D. Marino, plenary talk on optical transition radiation monitor at T2K, Aug. 2010.
6. Neutrino Beams and Instrumentation Workshop 2010 (Tokai, Japan): E. D. Zimmerman, plenary talk on T2K horn project, Aug. 2010.
7. Physics In Collision 2010 (Karlsruhe, Germany): M. J. Wilking, plenary review talk on Recent Neutrino Interaction Measurements, Sept 2010.
8. NNN 2010 (Toyama, Japan): E. D. Zimmerman, plenary talk on Recent Results from MiniBooNE, Dec. 2010.
9. NuInt 2011 (Dehradun, India): R. H. Nelson, plenary talk on Measurements of Single Pion Production at MiniBooNE, March 2011.
10. Rencontres de Blois 2011 (Blois, France): E. D. Zimmerman, parallel talk on Recent Results from MiniBooNE, May 2011.
11. FPCP 2011 (Maale Hachamisha, Israel): E. D. Zimmerman, plenary review talk on T2K and Future Neutrino Oscillation Measurements, May. 2011.
12. PANIC 2011 (Cambridge, MA): E. D. Zimmerman, parallel talk on Short Baseline Neutrino Physics at MiniBooNE, July, 2011.
13. Implications for Neutrino Flavor Oscillation (Santa Fe, NM): A. D. Marino, plenary talk on Run 1 and 2 results from T2K, July 2011.
14. Workshop on High Energy Physics Phenomenology '12 (Mahabaleshwar, India): E. D. Zimmerman, plenary review of neutrino oscillations, January 2012.
15. APS April 2012 Meeting (Atlanta, GA): R. A. Johnson, parallel talk on Inclusive Charged-Current ν_μ Analysis of the Pi-Zero Detector at T2K
16. PHENO'12 Symposium (Pittsburgh, PA): E. D. Zimmerman, plenary review of neutrino oscillations, May 2012.
17. CIPANP 2012 (St. Petersburg, FL): A. D. Marino, parallel talk on results from accelerator-based neutrino experiments, June 2012.
18. Annual Meeting of the Four Corners Section of the APS (Socorro, NM) A. D. Marino, invited talk on T2K results, October 2012.
19. Neutrino Beams and Instrumentation Workshop 2012 (CERN): E. D. Zimmerman, talk on MiniBooNE beamline; S. J. Coleman, talk on T2K horns; A. D. Missert, talk on T2K horn field measurements (all plenary), November 2012.
20. Workshop on Flux Measurement and Determination in the Intensity Frontier Era Neutrino Beams (Pittsburgh, PA) A. D. Marino, plenary talk on T2K results, December 2012.
21. Rencontres de Physique de la Vallée d'Aoste (La Thuile, Italy): S. J. Coleman, plenary talk on T2K results, February 2013.
22. APS April Meeting (Denver, CO): D. Poulson, parallel talk on LBNE muon monitoring, April 2013.

3.3 Seminar and Colloquium Talks

1. A. D. Marino, seminar at Argonne National Lab, April 2010.
2. A. D. Marino, colloquium at Colorado State University, May 2010.
3. A. D. Marino, colloquium at Colorado School of Mines, January 2011.
4. A. D. Marino, seminar, Lawrence Berkeley National Laboratory, February 2011.
5. A. D. Marino, seminar, University of Maryland, February 2012.
6. A. D. Marino, colloquium at Virignia Tech, April 2012.
7. E. D. Zimmerman, seminar at University of Chicago, October 2011.
8. E. D. Zimmerman, seminar at UC Davis, November 2011.
9. E. D. Zimmerman, colloquium at Kansas State University, February 2012.
10. E. D. Zimmerman, colloquium at Colorado State University, March 2012.
11. E. D. Zimmerman, colloquium at Michigan State University, September 2012.
12. E. D. Zimmerman, colloquium at University of Colorado, September 2012.
13. E. D. Zimmerman, seminar at TRIUMF, November 2012.

4 List of Colorado Theory Publications and Talks

4.1 List of Publications

The following publications were written by members of our group in the last three years.

1. S. Catterall, P. H. Damgaard, T. Degrand, R. Galvez and D. Mehta, "Phase Structure of Lattice N=4 Super Yang-Mills," JHEP **1211** (2012) 072 [arXiv:1209.5285 [hep-lat]].
2. J. Beringer *et al.* [Particle Data Group Collaboration], "Review of Particle Physics (RPP)," Phys. Rev. D **86** (2012) 010001.
3. T. DeGrand, "Lattice baryons in the 1/N expansion," Phys. Rev. D **86** (2012) 034508 [arXiv:1205.0235 [hep-lat]].
4. T. DeGrand, "Log-normal distribution for correlators in lattice QCD?," Phys. Rev. D **86** (2012) 014512 [arXiv:1204.4664 [hep-lat]].
5. T. DeGrand, Y. Shamir and B. Svetitsky, "SU(4) lattice gauge theory with decuplet fermions: Schrodinger functional analysis," Phys. Rev. D **85** (2012) 074506 [arXiv:1202.2675 [hep-lat]].
6. T. DeGrand, Y. Shamir and B. Svetitsky, "Mass anomalous dimension in sextet QCD," Phys. Rev. D **87**, 074507 (2013) arXiv:1201.0935 [hep-lat].
7. T. DeGrand, Y. Shamir and B. Svetitsky, "Gauge theories with fermions in the two-index symmetric representation," PoS LATTICE **2011** (2011) 060 [arXiv:1110.6845 [hep-lat]].
8. T. DeGrand, "Finite-size scaling tests for spectra in SU(3) lattice gauge theory coupled to 12 fundamental flavor fermions," Phys. Rev. D **84** (2011) 116901 [arXiv:1109.1237 [hep-lat]].
9. T. DeGrand, Y. Shamir and B. Svetitsky, "Infrared fixed point in SU(2) gauge theory with adjoint fermions," Phys. Rev. D **83** (2011) 074507 [arXiv:1102.2843 [hep-lat]].

10. K. Nakamura *et al.* [Particle Data Group Collaboration], "Review of particle physics," J. Phys. G **37** (2010) 075021.

11. T. DeGrand, "Lattice studies of QCD-like theories with many fermionic degrees of freedom," arXiv:1010.4741 [hep-lat].

12. B. Svetitsky, Y. Shamir and T. DeGrand, "Sextet QCD: slow running and the mass anomalous dimension," PoS LATTICE **2010** (2010) 072 [arXiv:1010.3396 [hep-lat]].

13. D. Schaich, A. Cheng, A. Hasenfratz and G. Petropoulos, "Bulk and finite-temperature transitions in SU(3) gauge theories with many light fermions," PoS **Lattice 2012**, 028 (2012) [arXiv:1207.7164 [hep-lat]].

14. A. Hasenfratz, A. Cheng, G. Petropoulos and D. Schaich, "Mass anomalous dimension from Dirac eigenmode scaling in conformal and confining systems," PoS **Lattice 2012**, 034 (2012) [arXiv:1207.7162 [hep-lat]].

15. A. Hasenfratz, "MCRG study of 12 fundamental flavors with mixed fundamental-adjoint gauge action," PoS **Lattice 2011**, 065 (2011) arXiv:1112.6146 [hep-lat].

16. A. Cheng, A. Hasenfratz and D. Schaich, "Novel phase in SU(3) lattice gauge theory with 12 light fermions," Phys. Rev. D **85**, 094509 (2012) [arXiv:1111.2317 [hep-lat]].

17. A. Hasenfratz, "Infrared fixed point of the 12-fermion SU(3) gauge model based on 2-lattice MCRG matching," Phys. Rev. Lett. **108**, 061601 (2012) [arXiv:1106.5293 [hep-lat]].

18. A. Li *et al.* [xQCD Collaboration], "Overlap Valence on 2+1 Flavor Domain Wall Fermion Configurations with Deflation and Low-mode Substitution," Phys. Rev. D **82**, 114501 (2010) [arXiv:1005.5424 [hep-lat]].

19. A. Hasenfratz, "Conformal or Walking? Monte Carlo renormalization group studies of SU(3) gauge models with fundamental fermions," Phys. Rev. D **82**, 014506 (2010) [arXiv:1004.1004 [hep-lat]].

20. A. Hasenfratz, R. Hoffmann and S. Schaefer, "Epsilon regime calculations with reweighted clover fermions," PoS **LATTICE 2008**, 081 (2008) [arXiv:0810.0496 [hep-lat]].

21. A. Hasenfratz, R. Hoffmann and S. Schaefer, "Low energy chiral constants from epsilon-regime simulations with improved Wilson fermions," Phys. Rev. D **78**, 054511 (2008) [arXiv:0806.4586 [hep-lat]].

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23. Lattice Strong Dynamics Collaboration: T. Appelquist, R. C. Brower, M. I. Buchoff, M. Cheng, S. D. Cohen, G. T. Fleming, J. Kiskis, M. F. Lin, H. Na, E. T. Neil, J. C. Osborn, C. Rebbi, D. Schaich, C. Schroeder, G. Voronov and P. Vranas, "Approaching Conformality with Ten Flavors," arXiv:1204.6000 [hep-ph].

24. R. Brower, C. Rebbi and D. Schaich, "Hybrid Monte Carlo simulation on the graphene hexagonal lattice," PoS **Lattice 2011**, 056 (2011) [arXiv:1204.5424 [hep-lat]].

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26. D. Schaich [for the LSD Collaboration], "S parameter and parity doubling below the conformal window," PoS **Lattice 2011**, 087 (2011) [arXiv:1111.4993 [hep-lat]].

27. M. -C. Chen, K. T. Mahanthappa, A. Meroni and S. T. Petcov, "Predictions for Neutrino Masses, $\beta\beta_{0\nu}$-Decay and Lepton Flavor Violation in a SUSY $SU(5) \times T'$ Model of Flavour," arXiv:1109.0731 [hep-ph].

28. M. -C. Chen and K. T. Mahanthappa, "Leptogenesis in a SUSY SU(5) x T' Model with Geometrical CP Violation," arXiv:1107.3856 [hep-ph].

29. M. -C. Chen and K. T. Mahanthappa, "Models and Phenomenology of Neutrino Masses circa 2010," arXiv:1012.1595 [hep-ph].

30. M. -C. Chen and K. T. Mahanthappa, "Geometrical Origin of CP Violation and CKM and MNS Matrices in SU(5) x T'," PoS ICHEP **2010**, 407 (2010) [arXiv:1011.6364 [hep-ph]].

31. M. -C. Chen and K. T. Mahanthappa, "Tri-bimaximal (TBM) neutrino mixing and quark CKM matrix in a SU(5) x T-(d) model," J. Phys. Conf. Ser. **136**, 042021 (2008).

32. M. -C. Chen and K. T. Mahanthappa, "A novel origin of CP violation," Prog. Part. Nucl. Phys. **64**, 348 (2010).

33. M. -C. Chen, K. T. Mahanthappa and F. Yu, "A Viable Flavor Model for Quarks and Leptons in RS with T-prime Family Symmetry," AIP Conf. Proc. **1200**, 623 (2010) [arXiv:0909.5472 [hep-ph]].

34. M. -C. Chen and K. T. Mahanthappa, "A Novel Origin of CP Violation," AIP Conf. Proc. **1200**, 896 (2010) [arXiv:0909.5470 [hep-ph]].

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38. S. de Alwis and K. Givens, "Physical Vacua in IIB Compactifications with a Single Kaehler Modulus," JHEP **1110**, 109 (2011) [arXiv:1106.0759 [hep-th]].

39. S. P. de Alwis, "Constraints on LVS Compactifications of IIB String Theory," JHEP **1205**, 026 (2012) [arXiv:1202.1546 [hep-th]].

40. S. de Alwis and K. Givens, "Dark Matter density and the Higgs mass in LVS String Phenomenology," Phys. Lett. B **719**, 143 (2013) [arXiv:1203.5796 [hep-ph]].

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47. M. Cicoli, S. de Alwis and A. Westphal, “Heterotic Moduli Stabilization,” arXiv:1304.1809 [hep-th].
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51. C. M. Brown and O. DeWolfe, “The Godel-Schrodinger Spacetime and Stringy Chronology Protection,” JHEP **1201**, 032 (2012) [arXiv:1110.3840 [hep-th]].
52. O. DeWolfe, S. S. Gubser and C. Rosen, “Dynamic critical phenomena at a holographic critical point,” Phys. Rev. D **84**, 126014 (2011) [arXiv:1108.2029 [hep-th]].
53. O. DeWolfe, S. S. Gubser and C. Rosen, “A holographic critical point,” Phys. Rev. D **83**, 086005 (2011) [arXiv:1012.1864 [hep-th]].
54. A. Adams, O. DeWolfe and W. Taylor, “String universality in ten dimensions,” Phys. Rev. Lett. **105**, 071601 (2010) [arXiv:1006.1352 [hep-th]].

4.2 List of Conference Talks

1. T. DeGrand, Lattice studies of QCD-like theories with many fermionic degrees of freedom – invited talk at “Renormalization group and critical phenomena”, workshop at the Institute for Nuclear Theory, Seattle, February 2010
2. T. DeGrand, Gauge theories with fermions in the two-index symmetric representation – talk given at Lattice 2011, Lake Tahoe, July 2011
3. T. DeGrand, Gauge theories with 2, 3, 4 colors and 2 fermions in the two-index symmetric representation, talk at the Fermilab workshop “Lattice meets experiment,” October 2011
4. A. Hasenfratz, Introduction to Lattice QCD – four lectures at the INT summer school “Lattice Methods in Particle and Nuclear Physics”, Seattle, August 2012
5. A. Hasenfratz, Mass anomalous dimension from Dirac eigenmode scaling in conformal and confining systems – talk at the Lattice 2012 conference, Cairns, June 2012
6. A. Hasenfratz, A novel phase in many fermion systems – invited talk at the workshop “New Horizons for Lattice Computations with Chiral Fermions”, Brookhaven, May 2012
7. A. Hasenfratz, A novel phase in many fermion systems – invited talk at the workshop “Conformality in Strong Coupling Gauge Theories at LHC and Lattice”, Nagoya, March 2012
8. A. Hasenfratz, Infrared fixed point in the Nf=12 flavor SU(3) model – invited talk at the workshop “Lattice Meets Experiment: Beyond the Standard Model”, October 2011

9. A. Hasenfratz, MCRG study of pure gauge SU(2) mixed action model – poster at the Lattice 2011 conference, Squaw Valley, July 2011
10. A. Hasenfratz, Infrared fixed point in the Nf=12 flavor SU(3) model – parallel talk at the Lattice 2011 conference, Squaw Valley, July 2011
11. A. Hasenfratz, Reweighting in the quark mass – plenary talk at the Lattice 2011 conference, Squaw Valley, July 2011
12. A. Hasenfratz, Renormalization group in conformal and near-conformal field theories – four lectures at the Schladming 2011 Winter School, February 2011
13. A. Hasenfratz, Conformal or Walking? – presentation at "The Future of lattice QCD", CERN workshop, July 2010
14. A. Hasenfratz, MCRG methods – talk at the workshop "Strong Dynamics Beyond the Standard Model", Aspen Center for Physics, June 2010
15. A. Hasenfratz, Conformal or Walking? – talk at the workshop "Origin of mass", Odense University, May 2010
16. A. Hasenfratz, Renormalization group for BSM systems – invited talk at the INT workshop "New applications of the renormalization group method in nuclear, particle and condensed matter physics", Seattle, February 2010
17. D. Schaich, Bulk and finite-temperature transitions in SU(3) gauge theories with many light fermions – talk at the Lattice 2012 conference, Cairns, June 2012
18. D. Schaich, Novel phase in SU(3) lattice gauge theories with many light fermions – talk at the APS April Meeting, Atlanta, April 2012
19. D. Schaich, Lattice Strong Dynamics for the LHC – talk at the workshop "Conformality in Strong Coupling Gauge Theories at LHC and Lattice", Nagoya, March 2012
20. D. Schaich, The S Parameter on the Lattice – invited talk at the workshop "Lattice Meets Experiment: Beyond the Standard Model", Fermilab, October 2011
21. K.T. Mahanthappa, Geometrical origin of CP violation – invited talk at ICHEP 2010, Paris, France, July 2010
22. K. T. Mahanthappa, Geometrical origin of CP violation, and CKM and MNS matrices in SUSY $\times T'$ model – Symposium on Dark Matter and Neutrinos (Bengaluru, India) invited plenary talk, August 2011.
23. S. P. de Alwis, Invited talk at "Unification and String Theory" workshop at Bethe Centre Bonn, Germany, October 2012.
24. S.P. de Alwis, Plenary talk at "String Pheno 12", Cambridge, UK. June 2012
25. S. P. de Alwis, Plenary talk at "String Pheno 11", Madison WI, USA. August 2011
26. S. P. de Alwis, Invited talk "SPOCK" meeting University of Cincinnati, October 2010
27. S. P. de Alwis, Plenary talk at "String Pheno 10', Paris, France July 2010
28. S. P. de Alwis, Invited talk at Workshop on String phenomenology KITP, Santa Barbara, CA, USA May 2010
29. O. DeWolfe, Invited talk at Aspen Winter Conference on Strongly Correlated Systems and Gauge/Gravity Duality, Aspen Center for Physics, February 2011.

30. O. DeWolfe, Invited talk at Jet Tomography vs Holography of the Quark Gluon Plasma at RHIC vs LHC meeting, Columbia University, October 2011.

4.3 List of Seminar and Colloquium Talks

1. T. DeGrand, The s-parameter in a walking theory – seminar at the CERN theory institute on "Future directions in lattice gauge theory," July 2010
2. T. DeGrand, Strongly coupled beyond - Standard Model physics on the lattice – seminar at New Mexico State U., October 2010
3. T. DeGrand, First principles calculations for the strong interactions? – Colloquium at New Mexico State U., October 2010
4. T. DeGrand, "Symmetric representation fermions at (not so) large N" – seminar at the Galileo Galilei Institute Workshop on Large-N gauge theories, Florence, May 2011
5. T. DeGrand, Technicolor meets the lattice – seminar at Brookhaven National Lab, February 2012
6. T. DeGrand, Checking technicolor candidates using the lattice – seminar at the University of Maryland, April 2012
7. T. DeGrand, Log-normal distribution for correlators in lattice QCD? – seminar at the Niels Bohr Institute, August 2012
8. T. DeGrand, Supersymmetry on the lattice – seminar at Triumf, November 2012
9. T. DeGrand, Lattice baryons in the $1/N$ expansion – Seminar at JLAB, April 2013
10. A. Hasenfratz, A novel phase in many fermion systems, seminar at Suny Stony Brook, May 2012
11. A. Hasenfratz, Finite temperature studies in many fermion systems, "SciDac allhands meeting", FNAL, May 2012
12. A. Hasenfratz, A novel phase in many fermion systems, seminar at BNL, April 2012
13. A. Hasenfratz, A novel phase in many fermion systems, seminar at KITP Santa Barbara, Feb 2012
14. A. Hasenfratz, Strongly coupled systems, colloquium at Virginia Tech, Oct 2011
15. A. Hasenfratz, MCRG for 12 flavors, "SciDac allhands meeting", JLab, May 2011
16. A. Hasenfratz, Conformal or Walking? – seminar at Eotvos University, Budapest Hungary, May 2011
17. A. Hasenfratz, Strongly coupled systems –colloquium at University of Iowa, Nov. 2010
18. A. Hasenfratz, Conformal or Walking? – seminar at University of Iowa, Nov. 2010
19. A. Hasenfratz, Strongly coupled systems – colloquium at Reed College, Oregon, Oct. 2010
20. A. Hasenfratz, Conformal or Walking? – seminar, INLN Frascati, Rome, July 2010
21. A. Hasenfratz, Conformal or Walking? – seminar, Niels Bohr Inst, Copenhagen, May 2010
22. A. Hasenfratz, MCRG methods, "SciDac allhands meeting", BNL, Apr 2010
23. A. Hasenfratz, MCRG methods, seminar at UCSD, March 2010

24. A. Hasenfratz, Strongly coupled systems – colloquium at University of Connecticut, Storrs, Feb. 2010
25. A. Hasenfratz, MCRG methods, seminar at Yale, Feb. 2010
26. K.T. Mahanthappa, Geometrical origin of CP violation, and CKM and MNS matrices in SUSY Y $\times T'$ model – seminar at Oklahoma State University, October, 2010
27. K.T. Mahanthappa, Masses and mixing angles of quarks and leptons and a novel origin of CP violation – colloquium at Oklahoma State University, October, 2010
28. K.T. Mahanthappa, Geometrical origin of CP violation, and CKM and MNS matrices in SUSY Y $\times T'$ model – seminar at University of Maryland, March 2012
29. S.P. de Alwis, "Higgs mass, dark matter density, and SUSY breaking in LVS string models" University of Padova, Italy, March 2013
30. S.P. de Alwis, "SUSY breaking and mediation in LVS string models" University of Rome "Tor Vagata", Italy, April 2013
31. S.P. de Alwis, "SUSY breaking and mediation in string models" University of Bologna, Italy, May 2013
32. S.P. de Alwis, Some issues in SUSY breaking, University of Hamburg and DESY, July 2012
33. S.P. de Alwis, Some issues in SUSY breaking, Technical University of Munich, July 2012
34. S.P. de Alwis, Some issues in SUSY breaking, University of Heidelberg, July 2012
35. S. P. de Alwis, A local evaluation of global issues, ICTP Trieste, July 2011
36. O. DeWolfe, seminar at Stanford University, December 2011.

Appendix 2

Bibliography

BaBar References

[1] **Observation of CP violation in the B^0 meson system**, B. Aubert *et al.* (*BABAR* Collaboration), *Phys. Rev. Lett.* **87**(2001), 091801.

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[3] **Direct CP Violating Asymmetry in $B^0 \to K^+\pi^-$ Decays**, B. Aubert *et al.* (*BABAR* Collaboration), *Phys. Rev. Lett.* **93**(2005), 131801.

[4] **Improved Measurement of the Cabibbo-Kobayashi-Maskawa Angle α Using $B^0(\overline{B}^0) \to \rho^+\rho^-$ Decays**, B. Aubert *et al.* (*BABAR* Collaboration), *Phys. Rev. Lett.* **95**(2005), 041805; **A Study of $B^0 \to \rho^+\rho^-$ Decays and Constraints on the CKM Angle α** , B. Aubert *et al.* (*BABAR* Collaboration), *Phys. Rev. D* **76**(2007), 052007.

[5] **Observation of CP violation in $\mathcal{B}(B^0 \to \eta' K^0)$ Decays**, B. Aubert *et al.* (*BABAR* Collaboration), *Phys. Rev. Lett.* **98**(2007), 031801.

[6] **B-meson decays to $\eta'\rho$, $\eta' f_0$, and $\eta' K^*$** , P. del Amo Sanchez *et al.* (*BABAR* Collaboration), *Phys. Rev. D* **82**(2010), 011502.

[7] **Inclusive B-meson decays to K^+, K^0_S, and π^+**, P. del Amo Sanchez *et al.* (*BABAR* Collaboration), *Phys. Rev. D* **83**(2011), 031103.

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[11] **Polarization in B Decays**, A. V. Gritsan and J. G. Smith, Reviews of Particle Properties,, *Phys. Rev. D* **86**(2012), ,1060.

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[18] CMS Collaboration, *CMS tracking performance results from early LHC operation*, Eur. Phys. J. C **70**, 1165 (2010).

[19] CMS Collaboration, *Strange Particle Production in pp Collisions at $\sqrt{s}$ = 0.9 and 7 TeV,* JHEP **1105**, 064 (2011).

[20] CMS Collaboration, *Measurement of the B^0 production cross section in pp Collisions at $\sqrt{s}$ = 7 TeV,* Phys. Rev. Lett. **106**, 252001 (2011).

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[32] J. Cumalat, E. Luiggi *et al.*, *Search for Heavy Resonances Decaying to Tau Pairs in CMS*, CMS-AN-11-007.

[33] J. Cumalat, E. Luiggi *et al.*, *Search for Heavy Resonances Decaying to Di Tau States*, CMS-AN-11-236.

[34] C. Edelmaier, W. T. Ford, J. G. Smith *et al.*, *SUSY multilepton searches with electrons, muons, and taus*, CMS-AN-10-231.

[35] C. Edelmaier, W. T. Ford, A. Gaz, J. G. Smith, K. A. Ulmer *et al.*, *Search for New Physics in Events with b-Jets and Missing Transverse Energy in 2011*, CMS-AN-11-257.

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