Final Technical Report for

"High Energy Physics at The University of Iowa"

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EXECUTIVE SUMMARY

Particle Physics explores the very fundamental building blocks of our universe: the nature of forces, of space and time. By exploring very energetic collisions of sub-nuclear particles with sophisticated detectors at the colliding beam accelerators (as well as others), experimental particle physicists have established the current theory known as the Standard Model (SM), one of the several theoretical postulates to explain our everyday world. It explains all phenomena known up to a very small fraction of a second after the Big Bang to a high precision; the Higgs boson, discovered recently, was the last of the particle predicted by the SM. However, many other phenomena, like existence of dark energy, dark matter, absence of anti-matter, the parameters in the SM, neutrino masses etc. are not explained by the SM. So, in order to find out what lies beyond the SM, i.e., what conditions at the earliest fractions of the first second of the universe gave rise to the SM, we constructed the Large Hadron Collider (LHC) at CERN after the Tevatron collider at Fermi National Accelerator Laboratory. Each of these projects helped us push the boundary further with new insights as we explore a yet higher energy regime. The experiments are extremely complex, and as we push the boundaries of our existing knowledge, it also requires pushing the boundaries of our technical knowhow. So, not only do we pursue humankind's most basic intellectual pursuit of knowledge, we help develop technology that benefits today's highly technical society. Our trained Ph.D. students become experts at fast computing, manipulation of large data volumes and databases, developing cloud computing, fast electronics, advanced detector developments, and complex interfaces in several of these areas. Many of the Particle physics Ph.D.s build their careers at various technology and computing facilities, even financial institutions use some of their skills of simulation and statistical prowess. Additionally, last but not least, today's discoveries make for tomorrow's practical uses of an improved life style, case in point, internet technology, fiber optics, and many such things. At The University of Iowa we are involved in the LHC experiments, ATLAS and CMS, building equipment, with calibration and maintenance, supporting the infrastructure in hardware, software and analysis as well as participating in various aspects of data analyses. Our theory group works on fundamentals of field theories and on exploration of non-accelerator high energy neutrinos and possible dark matter searches.

Final Report of TASK A

Until the recent modification in the DOE peer review policy, The University of Iowa had an umbrella grant; subsequently, it has been split into two experimental and one theory grants. The current report is what previous Task A group led by Usha Mallik achieved with the grant since 1990. The highlights of the research accomplishments of Task A are listed below by the years and the experiments except the latest one.

- **1990-1991** MARKIII experiment: Study of the charm quark and its decays; part of thesis of graduate student Min-Zu Wang[19] published[1], highly cited.

- **1989-1998** ZEUS experiment: Study of the inner structure of proton; (1989-1991) testbeam experiment E790 to test and calibrate ZEUS calorimeter readout electronics and barrel calorimeter modules in-situ. Deputy Spokesperson of E790. The second half of Min-Zu Wang's Ph.D. thesis: experimental setup, the data taking and the analysis. Jun Wu: Master's degree from E790. Results published[2] and presented at several conferences[3].

  Moved to DESY laboratory in Hamburg. With group responsible for the calorimeter calibration, online calorimeter software coordinator; Data Validation coordinator for the first year data; Ph.D. thesis of Maria Roco[19] on the first determination of the gluon momentum density at low$x$[4]. Responsible for calibration, data collcetion and analysis for the prototype of Presamplers for Forward and the Rear calorimeters with students S-M. Wang and J-T. Wu. Construction of 14-layer digital electronics boards for the Presamplers. Results from a new qualitative determination of gluon momentum density, by using the heavy quark scale for perturbative calculation to be valid following ideas by RysKin; used elastic production of J/ψ as a measure of $xg(x)$, with publication[5]. Earned APS fellowship from the Division of Particle and Fileds (DPF). Ph.D. thesis of J-T Wu (1997) on Deep Inelastic Production of vector bosons based on similar principles[6], and Ph.D. thesis of S-M Wang[19] (1998) on inelastic production of J/ψ[7], both published.

- **1996-2008** BaBaR experiment: to understand the mystery of the extreme asymmetry between matter and antimatter in our universe by exploring CP-violation in heavy quarks. Served as Online Trigger Software coordinator, Run-coordinator; group members Rainer Bartoldus[19] as Trigger commissioner, Trigger coordinator; Gerald Grenier[19] responsible for Level 1 trigger core software, Level 1 trigger upgrade software. Leading role in Charmed Baryon physics, first observation of Ω_c production from B-meson decays[8], first observation (jointly with SUNY Albany group) of the Ω_c^*[9], only remaining $(3/2)^+$ ground state $SU_f(4)$; graduate student Veronique Ziegler[19], measured the spin-parity of the Ω^-[10] measured decay properties and spin-parities of several baryons[11], completing her Ph.D. in 2007. Other publications on measurements of Ξ_c and excited states[12], graduate stedent Xuedong Chai measured the exclusive decay of B-meson into $\Lambda_c\overline{\Lambda_c}$ and with an additional K-meson[13] completing his Ph.D. in 2008. Group member Mat Charles[19] served as the Charm analysis working group co-coordinator.

- **2003-2013** Future e^+e^- Linear Collider: To search what lies beyond Standard Model. Joined the R&D program of the SiD concept, one of the original ALCPG members, and initially responsible for the trigger and software for the Americas. Later with Mat Charles and Ron Cassell from SLAC developed a Particle Flow Algorithm (PFA); this Iowa PFA used by the SID concept for benchmarking all the physics processes for validation of the detector by the International Detector Advisory Group for a center-of-mass energy of 500 GeV. In late 2012 in collaboration with CLIC, the detector concept validated for 1 TeV energy, and performed a restructuring of the PFA with postdocs Remi Zaidan and Garabed Halladjian leading to large improvemnet in jet-jet resolution within the deadline for the Detailed Baseline Benchmark (DBD), though more can and should be done. Halladjian, Mallik and Zaidan presented the improvements at several recent international ILC workshops[14].

1 2006-2013: The ATLAS Experiment

Joined the ATLAS experiment in October 2006 as a sub-group of SLAC, by dividing up resources between BaBar and ATLAS. The Silicon Pixel sub-detector needed help. Prafulla Behera[19], an Assistant Research Scientist, and a new postdoc, Alex Schreiner, started working on the Pixel. Schreiner developed the DSP code necessary to perform calibration of the complete Pixel detector with 80 million pixel channels in parallel possible. In 2008 the Pixel detector was first placed in the ATLAS detector, Behera produced the first Pixel detector control system (DCS) essential to connect and operate the detector safely before the planned DCS software was implemented. By 2009 the group consisting of Behera, two new postdocs:Maaike Limper[19] and Remi Zaidan, and Mallik were at CERN.

The group worked on the following through 2010 :

Detector related topics

- In-situ calibration of the Pixel detector[15], Behera was an expert of the Threshold calibration procedure
- Cosmic ray data collection and analysis to understand the operation of the Pixel detector; Behera was responsible for establishing the Lorentz angle and the depletion depth from the data. In addition with two others he analyzed the threshold calibration data collected under various conditions and documeted these procedures and results
- The complete operation and calibration procedure as well as the results obtained from the cosmic ray data were documented; Mallik served on the committee of seven editors from the Pixel community
- Limper produced the necessary databases for the Pixel detector so that they could be generated, updated, maintained and accessed by offline reconstruction outside ATLAS control room
- Mallik and Behera served on the Pixel DAQ and normal Pixel shifts as well as SLIMOS shifts (safety and access) in ATLAS control room (ACR); Mallik served additionally as Shift leader and on Lumi shifts in ACR
- Limper served as a Prompt Reconstruction Coordinator (PROC) for six months; two PROCs cover the responsibility of seeing the data collected by ATLAS is processed in the proper data streams and a fraction is quickly processed to provide calibration files for the particular dataset. They are responsible to verify that the nightly updates from all systems are in proper working order

Software related topics

- Limper worked on extending track reconstruction below 500 MeV/c with the tracking experts and in validating it. It was validated down to 100 MeV/c in momentum

- Zaidan prepared the data summary prescription from the reconstructed data according to ATLAS software guidelines so that the first results could be obtained in a timely manner; it is serves as current trcaking part of the summary data and Zaidan is the expert for its maintenance
- Behera produced and setup the system to obtain the summary tapes through the worldwide grid from early data taking using Zaidan's software
- Zaidan and Behera worked on validating tracking and vertexing of ATLAS reconstruction from the early data

Physics related topics

- Before data taking started we worked on the Computing System Commissioning (CSC) from simulated data for SUSY in 0-lepton and on Minimum Bias studies
- We were involved with high level Minimum Bias trigger
- Behera, Limper and Zaidan played a central role in preparing, validating and testing the tools and software needed for the first data analysis, namely, for Minimum Bias physics
- They also played a central role in analysis of the Minimum Bias data for the very first ATLAS publication and the second and more comprehensive Minimum Bias publication later; this established charged multiplicity rates at 7 TeV energy[16]
- For the second more comprehensive publication Zaidan provided a second independent analysis for cross-checking the original analysis and provided corrections in the estimate of the systematic uncertainties

Several ATLAS CONF notes and internal notes were prepared from the above studies. In 2009 The University of Iowa group became an independent institution in the ATLAS collaboration.

1.1 The last three years: 2010-2012

Through 2010 Behera, Limper and Zaidan completed two publications on Minimum Bias, the latter one also included the low p_T tracks, with Zaidan producing an independent analysis which, helped the mainstream analysis by correcting it at times.

Behera and Limper were replaced by new recruits, Garabed Halladjian (to primarily work on the PFA with Zaidan) and Yuriy Pylypchenko. Zaidan worked on improving the b-tagging algorithm efficiency also with the high pile-up rate (multiple interactions) with increased luminosity.

In 2011 the luminosity delivered by LHC was vastly improved and this increased the pile-up rate as well. Garabed took on understanding the energy scale of the ATLAS calorimeter in the complex, overlapping events (high pile up) that characterize high luminosity running at the LHC which required a proper statistical treatment of the background present in each event. All of the systematic uncertainties had to be reevaluated following an order of magnitude increase in luminosity. Using single tracks Garabed provided an in-situ calibration method and the various independent components, presenting his results in the ATLAS Jet/Etmiss meetings as well as at the 2012 October ATLAS Hadronic Calibration Workshop[17]. He was requested to take charge of the publication resulting from E/p single hadron response. Recently, he has also been asked by the Jet/Etmiss conveners to continue to lead the single particle analysis with a few young people who could carry on the calibration method under his guidance.

The ATLAS collaboration wanted to upgrade the Pixel detector by inserting an extra layer closest to the beam pipe, named the Insertable B-layer (IBL). Our group had the construction, test, debug and calibration responsibility for the Low Voltage Patch Panel 4 (LVPP4) which supplies all low voltages needed for the Pixel Detector Control System (DCS). This was funded by an MRI grant from the NSF. We successfully provided the prototype in December 2012 for the current ongoing test for IBL, a postdoc setup a test bench at CERN with DCS software for test and calibration of all LVPP4 modules. The rest of the LVPP4 are being completed at Iowa.

1.2 Contribution to ATLAS Physics

The Minimum Bias physics established the physics performance tools (e.g., tracking and vertexing) by comparing real data with simulations, understanding the proper amount of detector material by validating the tracking and vertexing performances.

1.2.1 Higgs boson decay into $b\bar{b}$

As our next Physics analysis we concentrated on Higgs boson search in b-bbar decay mode where the H is accompanied by a vector boson (Z/W), where the Z decays into two charged leptons and the W into a single charged lepton with missing p_T. This helped us reduce the huge backgrounds, the single top and Z/W produced with heavy quarks. Dominating ones are from t-tbar, W/Z + b jets, di-boson production, and multijet processes; other backgrounds are from W/Z + light jets, W/Z + c jets, single tops etc. depending on the numbers of leptons present in the analysis channels.

Even though a preliminary result was submitted to the HCP conference[18], we (HSG5, the Higgs decay into b-bbar group) are working on submitting preliminary results with the complete data collected so far with an improved analysis. Because of the very small signal, the uncertainties have to be very carefully propagated in determining the various backgrounds using the control regions. The primary systematic uncertainties arise from jet energy scale and resolution, heavy flavor tagging and the mistag rates. A non-trivial amount is also attributed to modeling and difference between the LO and NLO calculations for the backgrounds.

The Iowa group is also involved in a Multi-Variate Analyses (MVA), specifically, a Boosted Decision Tree (BDT). Although a complete BDT has been pursued and setup, our first goal is to compare the results from a selected region of phase space with those obtained from the cut-based analysis. This will serve as a cross-check paving the way for a compelte BDT analysis to follow for a publication.

Zaidan and Halladjian developed the BDT tools and the training procedure; together with the Freiburg group they decided on 13 independent variables for the WH analysis. Several control regions are studied.

Modeling of the background processes from the MC simulation did not match the data perfectly. Additionally, understanding the b and c-jet tagging and light jet rejection efficiencies were critical. Some background processes did not have sufficient statistics to study. In addition, the QCD multi-jet processes could not be modeled from simulation. Like the cut-based analysis, several control regions (CR) are used. A lot of these studies were and are being performed.

Three notes are in preparation, the first note is common to the cut-based and the BDT analyses. The second note describes only the aspects specific to the cut-based analysis, and the third note describes the same for the BDT analysis. Zaidan is one of the two main editors of the BDT note.

1.2.2 ATLAS Support

- Shift Taking: There are quotas for operations tasks (OTP) required of each collaborator divided into class 1 (shifts in control room), class 2 (monitoring), and class 3 (experts) shifts. At present we are a bit short on class 2 shift category, which we plan to rectify before the year end. Both Limper and Zaidan accrue class 3 credit for the group. Mallik has collected the bulk of class 1 OTP credits.

- PAT D3PD: Zaidan continues to serve in the role of the ATLAS D3PD expert for tracking; in addition, he is the liaison between the Tacking combined performance group and the Physics analysis tools group. He earns class 3 OTP credit for both.

- ATLAS DAQ Operation: Limper was the Prompt Reconstruction Coordinator (PROC), an important position, completing in the end of August in 2011. The two PROCs take care of the ATLAS production software release used for reconstruction at the Tier0 at CERN. An express stream from the freshly collected data produces the necessary calibration constants for bulk processing.

- Pixel DSP work: Graduate student Reddy Pratap Gandrajula worked on Pixel DSP coding with two others to diagnose and categorize any abnormal behavior of the Pixel modules during data taking in order to understand the failures and if possible, to reduce them.

1.3 Upgrade work with the Insertable b-layer (IBL)

We are responsible for the Low Voltage Patch Panel 4 (LVPP4) construction, debugging and implementing in the Pixel DCS with PVSS software framework. A set of three cards, an opto-isolator board, an inter board and a front panel have been designed and fabricated at Iowa and sent to CERN. The fourth card, the ELMB board which communicated with the DCS softare, is supplied by Wuppertal. After an early connectivity tests and calibration of these boards proved satisfactory, a complete prototype of the patch panel with the transformer, connectors and a new set of boards were shipped to CERN, tested and calibrated by Pylypchenko at the test bench for the LVPP4 set up. This crate was installed in the full test of the IBL. This was successful and then four LVPP4 assemblies were constructed as the production batch. A total of five LVPP4 crates are constructed where one of them will continue to be for the test bench.

2 Particle Flow Work for Linear Collider 2003-

The group was involved in the R&D of the Linear Collider detectors, initially in calorimetry and later in Particle Flow Algorithm. In 2009 the Iowa PFA was used to produce all the physics benchmark processes to validate the SiD concept at 500 GeV center-of-mass energy, this was the work of Mat Charles with help from Ron Cassell[19] from SLAC. Improvement of the PFA to 1 TeV cm energy needed a near complete overhaul of the Iowa PFA, because of large increase in the track multiplicities, which caused more comfusion with the previous algorithm that sufficed till 500 GeV. A three year funding was obtained via ALCPG, and Halladjian was hired to work on the PFA. He worked on it with Zaidan, and together they established an improved version for 1 TeV energy before the DPD deadline. Later ILC and CLIC joined together to form Linear Collider Consortium (LCC).

It has been a productive group in all of the experiemnts it has participated in.

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Maria Roco, Desy, Fermilab postdoc, now at Lucent Technology;
Song-Ming Wang, Professor at Academia Sinica, Taiwan;
Jia-Tai Wu, in software industry, CA;
Rainer Bartoldus, Physics Staff at SLAC National Laboratory;
Gerald Grenier, faculty member at University Claude Bernard, Lyon, Fr;
Veronique Ziegler, SLAC postdoc, now staff at Jefferson Laboratory;
Xuedong Chai, intern in Medical Physics;
Matthew Charles, STFC senior 5-year fellow, now Maitre de conference, Universite de Paris VI;
Prafulla Behera, Associate Professor, Indian Inst. of Tech., Chennai, India;
Maaike Limper, three-year technical fellow at CERN;
Ronald Cassell, Staff, SLAC, deceased 2012.

UNIVERSITY OF IOWA HIGH ENERGY PHYSICS – TASK B1

Introduction
This report summarizes our progress in Task B1, ending April 30, 2013.

Our High Energy Physics Program at the University of Iowa focuses on the CMS experiment at CERN. Our group has a decades-long tradition of funding through the Department of Energy, with experimental work at Fermi National Accelerator Laboratory, SSC, and CERN. Our group consists of two PI's; Professor Yasar Onel and Associate Professor Jane Nachtman, as well as two emeritus professors; Professors Ed Norbeck and Ed McCliment, and one adjunct assistant professor; Professor Ugur Akgun, who has a faculty position at Coe College in Cedar Rapids, Iowa. Our group has two junior research scientists; Dr. Kai Yi and Dr. Taylan Yetkin; and two post-doctoral research assistants, Dr. Burak Bilki (½ time with ANL)and Dr. Alexi Mestvirishvili. We have two engineers, Ianos Schmidt and Paul Debbins. We are also training several graduate students: Elif Albayrak, Warren Clarida, Anthony Moeller, Sercan Sen, James Wetzel, Emrah Tiras, Tim Harrington-Taber, Maksat Haytmuradov, Hasan Ogul, Kamuran Dilsiz, Suleyman Durgut, Victor Khristenko, Zhe Jia; and several undergraduate students: Garrett Funk, Tyler Kent, Johnathan Kingyon, David Southwick, Lincoln Adams, and Jared Corso.

Our group truly works as a team, and it is difficult to separate our deliverables and group members into divisions by an individual PI. Our faculty and postdocs work with particular students and on projects according to interest and availability, in pursuit of our overall mission of discovery physics at the energy frontier. Additionally, we have several adjunct members who work with our group as part of their own research program at other institutions. However, in order to follow the guidelines for this proposal, we give here the nominal division of our group under PI's Yasar Onel and Jane Nachtman. We do this generally based on which PI's grant provides support, and which PI is the faculty advisor. In the subsequent text we will clarify which members are working on specific projects.

Onel's group consists of junior research scientist Dr. Taylan Yetkin, post-docs Dr. Burak Bilki and Dr. Alexi Mestvirishvili, engineers Ianos Schmidt and Paul Debbins, graduate students Elif Albayrak (DOE funds), Warren Clarida(DOE funds), Anthony Moeller (university funds), and Emrah Tiras(international grant).

Nachtman's group (with funding source) consists of junior research scientist Dr. Kai Yi (current DOE grant) and graduate students James Wetzel (current DOE and internal or university funds), Tim Harrington-Taber (university funds), and Maksat Haytmuradov(current DOE and university funds).

The remaining graduate and undergraduate students listed in the first paragraph work in our group as a whole; they are currently funded by the University and/or internal grants and in the case of beginning graduate students, have not yet narrowed their choice of thesis topic and advisor. These students are: Hasan Ogul, Kamuran Dilsiz, Suleyman Durgut, Victor Khristenko. Graduate student Zhe (George) Jia is a computer science student and is funded by the university, and graduate student Sercan Sen is an internationally-funded student attached to our group at CERN.

In the years 1991-94 Y. Onel was involved in the GEM project. Supported by DOE/SSC and TNRLC funding, he concentrated on two GEM subsystem R&D programs, GEM calorimetry (scintillating barrel and quartz fiber forward calorimetry) and a generic R&D experiment (RD-17) at CERN. He joined the CMS collaboration in March 1994, prompted primarily by the exciting physics prospects CMS offers, but also by the opportunity to apply the quartz fiber expertise gained from his previous GEM work.

The contribution of the Iowa CMS group to the HCAL has been significant. To summarize, we designed and constructed an HF EM calorimeter prototype, HF Radiation Damage (raddam) module and HF PPP1 (preproduction prototype #1), evaluated candidate PMTs for HF, prepared RFPs on both PMTs and fibers for HF, developed a test station to test the 2000+ PMTs purchased for HF, designed and purchased light-guide material for the HF, built PMT bases for HF, and built LED drivers for HCAL subsystems. Finally, we installed and commissioned the HF. Our group members have given several invited talks in the past three years at international conferences. We are also working on several R&D projects for SLHC and Lepton Collider detectors.

Jane Nachtman moved to the University of Iowa in August 2007, after holding a Wilson Fellowship and Scientist I positions at Fermilab, where she was on the CDF experiment. On CDF she supervised students (graduate, undergraduate, high school students), was the convenor of the Exotics Physics group, and provided operations support as a member of the data acquisition team. She joined CMS in 2007 with Yasar Onel's existing group. On CMS she has focused on building our physics program as well as upgrades of the HCAL, specifically the front-end electronics upgrade, with a program of simulation studies as well as prototyping. Her group has provided simulation and data studies for the HF upgrade.

Our postdoc at CERN Kerem Cankocak has moved to a tenured job as Associate Professor at ITU (Istanbul Technical University), Turkey. He recently became a member of the CMS Collaboration with his eight member group, and will collaborate with our current and future activities in CMS. Our Adjunct Assistant Professor Ugur Akgun has moved to a tenure-track faculty position at Coe College, Cedar Rapids. Both Kerem and Ugur continue with their UI association as Adjunct Scientists.

In the past year we have promoted two of our post-docs to junior research scientists. This move reflects their increased responsibilities and stature as leaders in our group. Both are actively seeking their next job; this position is not a career path for either of them. Dr. Taylan Yetkin has led the HCAL operations effort at CERN for several years, including positions as Operations Field Manager and HCAL Operations Expert. He is currently the Integration Co-coordinator for the HCAL Upgrade. Dr. Kai Yi is leading the physics effort for our group. He has spearheaded the dijet analysis effort from Iowa, and is currently managing and participating in three analyses, supervising three Iowa graduate students. His history of innovation and drive in physics analysis, and his burgeoning leadership ability, merited his promotion to junior research scientist.

In this proposal we are applying to the Proton program for funding of our CMS effort which includes physics analysis as well as detector operation and maintenance, and work on the CMS upgrade program.

Physics Program Summary

In the past three years under our DOE grant, we have contributed to the commissioning and successful operation of the CMS detector and are building our physics program, having completed several physics analyses resulting in publication. The thesis analyses of students Elif Albayrak ("Search for Supersymmetry in Jets and Missing ET"") and Warren Clarida ("Search for Heavy Majorana Neutrinos") have been published. We have established our group in the multijet analyses suite, beginning with taking on a supporting role in the first CMS Exotics publication. The search for new physics in the dijet mass spectrum was considered an early discovery analysis in the CMS physics program; our group contributed to this analysis as well as the dijet centrality ratio analysis, and then built on those to other dijet-based analyses, including a b-tagged dijet search and a paired dijet mass search. Our group has also made contributions to Forward Physics publications, using our unique expertise and understanding of the Forward Hadronic (HF) calorimeter. Transverse energy flow in such a very forward region, never measured before in hadron-hadron collisions, is directly sensitive to the amount of gluon radiation in the initial state, as well underlying event and multi-parton interactions.

A successful program on CDF led by our post-doc Dr. Kai Yi yielded the observation of a new and unexpected particle, the Y(4140), in a search of the J/Psi phi mass spectrum from exclusive B decays. This original analysis arose from his years of experience on BaBar and CDF, and subsequently led to our group establishing a spectroscopy program on CMS. Dr. Yi, along with graduate student Warren Clarida, made the first observation of X(3872) at CMS, an important benchmark in the validation of CMS as a viable detector for spectroscopic analysis. Dr. Yi also began a search of the J/Psi Phi mass spectrum in the CMS data, along with graduate student Elif Albayrak. This analysis will resolve the controversy due to results reported by LHCb, and will in addition lead to evidence of additional new particles. These are really a new type of particles, not explained by current theory. This difficult analysis was possible due to the unique expertise of Dr. Kai Yi, and has attracted much community interest to CMS and to our group. Our spectroscopy effort also includes a search for □ meson production in Y(2S) to $J/\psi\ \pi^+\pi^-$ at CMS (led by postdoc Dr. Burak Bilki) and a study of Upsilon production led by Dr. Alexi Mestvirishvilli.

The HF and HCAL effort
Our main focus on the HCAL concerns the PMT system calibration, optics design, quartz fibers, and radiation damage studies. We are also involved in the LED monitoring and radioactive source calibration systems for the entire hadron calorimeter. We will outline Iowa's recent progress in contributing to this elegant and detailed design of HF in our progress report.

The University of Iowa (Y. Onel) and Fairfield University (D. Winn) jointly proposed quartz fiber calorimetry for the CMS HF in January 1994 after prototyping quartz fiber calorimetry through SSC GEM Closeout funds. There are now six US and nine international institutions in the CMS HF group.

As the CMS detector is currently successfully collecting data, we are working on a program of upgrades for the HF. Yasar Onel is the Project Manager for the HF upgrade. Over the past several years, we have identified and tested a replacement PMT for the HF upgrade, and are currently in the final stages of testing and characterizing the ~2000 detectors needed for the HF. They are being shipped to CERN, where they will be installed in the HF starting in February 2013. Additionally we are involved in the front-end electronics upgrade for the HF, in specifying a pulse-time measurement for the readout chip. We are also participating in various simulation studies for the upgraded detector, both the HF and the HCAL as a whole. We have an established effort in R&D for the CMS upgrade detectors (PhaseI (LS1 and LS2) and Phase II (LS3)), in which we have developed new materials and techniques of calorimetry.

University of Iowa- Leadership positions in CMS HCAL- FY10 to FY12
Several members of our group have recently held or are currently holding leadership positions within the CMS, USCMS, and LPC management structure:

Y. Onel: L3 manager for HCAL Photodetectors and SLHC Quartz Plate Calorimeter Phase II Upgrade coordinator, HF Upgrade Project Manager PM for Phase I.
J. Nachtman: was LPC di-jet co-coordinator and the CMS calorimeter trigger upgrade co-coordinator, Performance and Simulation Coordinator for HCAL Phase I Upgrades.
T. Yetkin: was DPG Prompt Analysis co-coordinator as well as HCAL ROC co-coordinator, HCAL Operation Coordinator and CMS Field Manager; currently L2 Co-Manager for HCAL Integration group
I. Schmidt: HF Integration Engineer and CMS Forward Region Technical Coordinator.
K.Yi: HCAL Prompt Analysis Coordinator and liaison between CMS PFG and HCAL PFG.
K. Cankocak: was DPG Data Validation co-coordinator, HCAL Coordinator for Calibration Systems.
A. Mestvirishvili: HCAL System Operations Support.
W. Clarida: HCAL ROC coordinator at FNAL/LPC

University of Iowa Lifetime Awards on CMS Several Iowa group members have made key contributions and were rewarded with CMS Lifetime Awards. In 2010, our three engineers received this award: Ianos Schmidt for the HF design and engineering, construction of optics, fibers, and light guides; Paul Debbins received for Hadronic Barrel (HB), Hadronic Endcap (HE) and HF Source Drivers and Zero Degree Calorimeter (ZDC) design and construction; and Mike Miller for HCAL and HF LED system, HF parallel dynode base system, and HO interface electronics boards. In 2011, Taylan Yetkin received a CMS Lifetime Award for Leadership in HCAL Operations.

PUBLICATIONS IN WHICH OUR GROUP PLAYED A MAJOR ROLE

In addition to the following list of the most relevant publications from our group published in the past three years in refereed journals, we have contributed to numerous internal CMS notes as well as given many internal and conference presentations.

LEAD AUTHORSHIP / MAJOR CONTRIBUTIONS IN REFEREED JOURNAL

1. CMS Collaboration, ``Observation of Enhancements in the J/Psi Phi Mass Spectrum of Exclusive B+ to J/Psi Phi K+ Decays around 4148 and 4315 MeV/c^2'', in preparation.
2. CMS Collaboration, ``Search for Heavy Majorana Neutrino in Like-Sign Dileptons'', CMS PAS EXO-11-076, http://arxiv.org/abs/1207.6079, submitted to Phys. Lett. B.
3. CMS HCAL Collaboration, ``Tests of CMS Hadron Forward Calorimeter Upgrade Readout Box Prototype'', submitted to JINST
4. CMS Collaboration, ``Search for New Physics in the Multijet and Missing Transverse Momentum Final State in Proton-Proton Collisions at sqrt(s) = 7 TeV'', arXiv:1207.1898, submitted to Phys. Rev. Lett.
5. CMS Collaboration, ``Measurement of energy flow at large pseudorapidities in pp collisions at sqrt(s) = 0.9 and 7 TeV, JHEP 11 (2011) 148.
6. CMS Collaboration, "Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS, J. Instrum. 6 (2011) P11002.
7. CMS Collaboration, Missing Transverse Momentum in pp collisions at sqrt(s) = 7 TeV, JHEP 08 (2011) 155.
8. U. Akgun, *et al*., ``Boron and Thermal Neutron Interactions on Borosilica Window Photomultiplier Tubes'', JINST 5 P08005, 2010.
9. CMS HCAL Collaboration, ``Study of Various Photomultiplier Tubes with Muon Beams And Cerenkov Light Produced in Electron Showers'', JINST 5 P06002, 2010.
10. Q Zhang *et al* ., ``Environmental dependence of the performance of resistive plate chambers'', 2010 JINST 5 P02007 doi:10.1088/1748-0221/5/02/P02007
11. CMS Collaboration, ``Search for Dijet Resonances in 7 TeV pp Collisions at CMS'', Phys. Rev. Lett. 105, 211801, 2010.
12. CDF Collaboration, `` Evidence for a Narrow Near-Threshold Structure in the J/Psi Phi Mass Spectrum in B+ to J/Psi Phi K+Decays", Phys. Rev. Lett. **102**, 242002 (2009).
13. B.Bilki *et al.,*``Hadron showers in a digital hadron calorimeter'', JINST 4 P10008 2009.
14. B. Bilki *et al*.,``Measurement of the rate capability of Resistive Plate Chambers'', JINST 4 P06003 (2009).
15. B.Bilki *et al.,*``Measurement of positron showers with a digital hadron calorimeter'',JINST 4 P04006 (2009).

REVIEW ARTICLES AUTHORED

1. K. Yi, "Experimental Review of Structures in the J/Psi Phi Mass Spectrum'', to be submitted to Int. Journal of Mod. Phys. A.

2. J.L. Feng, J.F. Grivaz, J. Nachtman,``Searches for Supersymmetry at High-Energy Colliders'', Rev. Mod. Phys., Vol. 82, No. 1. January-March 2010.

LEAD AUTHORSHIP ON CMS PHYSICS ANALYSIS SUMMARY (PUBLICLY AVAILABLE FROM CMS OR CERN), CDF PUBLIC ANALYSIS NOTES

1. CMS Collaboration, ``Search for New Physics in Four-Jet Final States'', CMS PAS EXO-11-016.
2. CMS Collaboration, ``Search for Resonances with the Dijet Angular Ratio'', CMS PAS EXO-11-026.
3. CDF Collaboration, ``Observation of the Y(4140) structure in the J/Psi phi Mass Spectrum in B+ to J/Psi Phi K decays'', arXiv:1101.6058 .
4. CMS Collaboration, "Measurement of Energy Flow at Large Pseudorapidities in pp collisions at sqrt(s)=900, 2360, and 7000 GeV", CMS PAS FWD-10-002, (2010).

INTERNAL COLLABORATION PUBLICATION REVIEW COMMITTEES, INSTITUTIONAL REVIEW

1. CMS Collaboration, ``Measurement of the Inclusive Jet Cross Section in pp Collisions at sqrt(s) = 7 TeV'', Phys. Rev. Lett. **107**, 132001 (2011)
2. CDF Collaboration, ``Search for New Dielectron Resonances and Randall-Sundrum Gravitons at the Collider Detector at Fermilab'', Phys. Rev. Lett. **107**, 051801 (2011)
3. CMS Collaboration, ``Inclusive and Differential Measurements of the ttbar charge asymmetry in proton-proton collisions at sqrt(s)=7TeV'', arXiv:1207.0065, submitted to Phys. Lett. B.
4. CMS Collaboration**,** `` Search for electroweak production of charginos and neutralinos using leptonic final states in pp collisions at sqrt(s) = 7 TeV **'**', to be submitted to Phys. Lett. B.
5. CDF Collaboration, ``Measurement of the Cross Section for Prompt Isolated Diphoton Production in p-pbar Collisions at sqrt(s) = 1.96 TeV'', Phys. Rev.Lett. **107**, 102003 (2011).
6. CDF Collaboration, ``Measurement of the Cross Section for Prompt Isolated Diphoton Production in p-pbar Collisions at sqrt(s) = 1.96 TeV'', Phys. Rev. **D84**, 052006 (2011).
7. CDF Collaboration, `` Search for Randall-Sundrum Gravitons in the Diphoton Channel at CDF'', Phys. Rev. **D83** 011102 (2011).
8. CMS Collaboration, ``Search for Contact Interactions using Inclusive Jet Data at sqrt(s) = 7 TeV'', to be submitted to Phys. Rev. Lett.

PHYSICS AT THE ENERGY FRONTIER

Our CMS Physics Program focuses on discovery and encompasses several areas of our group's expertise. The previous success of our postdocs led to our current spectroscopy program. Our historical expertise in calorimetry and our years of effort on the HCAL led to a program of jet-based physics. Several graduate students are finishing their theses and publications; the results and future plans are given.

Spectroscopy Program

Search of the J/Psi phi mass spectrum and Discovery of a New Exotic Particle

Our Research Scientist, Dr. Kai Yi, originated the search of the J/Psi Phi mass spectrum at CDF. This analysis was done almost entirely by him, and resulted in the observation of a new particle, the Y(4140)[1] and hints of another particle at slightly higher mass. However, subsequent results from the LHCb collaboration refuted this claim[2]. Thus, Dr. Yi embarked on an independent search of the CMS data, in an environment where such measurements were not thought possible. Our confidence was bolstered by his earlier CMS analysis, along with Iowa graduate student Warren Clarida, which led to the first observation of the X(3872) at CMS. Dr. Yi brought the J/Psi Phi analysis to CMS, and with his expertise was able to establish hints of a signal. Graduate student Elif Albayrak joined this effort, and with this team Iowa has provided the driving leadership and main manpower for this analysis although there are other collaborators involved. Recently we have added another graduate student to this effort, second-year student Maksat Haytmuradov. Currently the documents available for this analysis are internal to CMS[3], but public release[4] is imminent and publication will follow shortly[5].

Our group has led the effort on this analysis, in leadership and vision as well as manpower invested. The signal that we search for is in the exclusive B decay mode, B+ → YK+,Y → J/ψφ ; we examine the J/ψφ mass spectrum. A clean B+ signal is essential, and our search necessitates a B sideband subtraction method. The B + signal before sideband subtraction is shown in Figure 1 (left) and the **mass o**f the K+K- system (φ) after B sideband subtraction is shown in Figure 1 (center). The obtained B yield is 2342 ± 158 (stat); this is the largest exclusive $B^+ \rightarrow J/\psi K^+K^-K^+$ sample in the world.

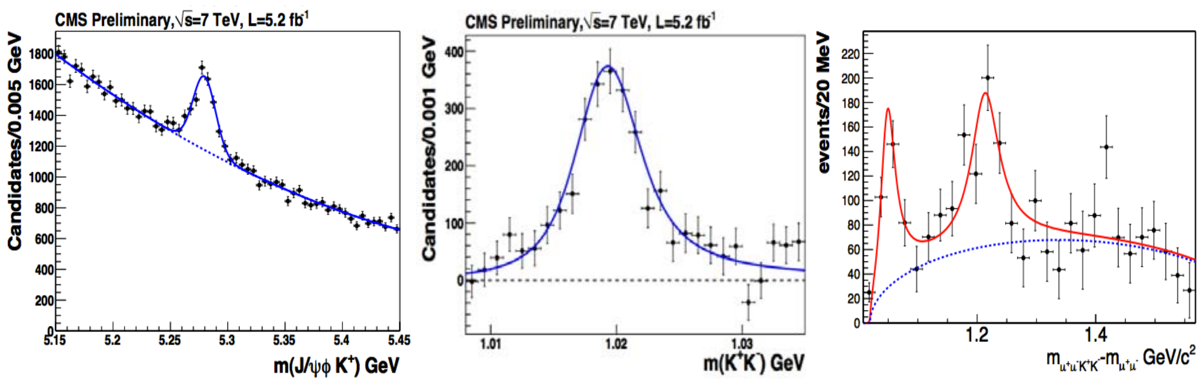

Figure 1 In the search for exotica in the B+ → J/ψφ system, (left) the invariant mass of the J/ψφ K system before B sideband subtraction. (center) The mass of the K+K- (φ) after B sideband subtraction. (right) The J/ψφ mass spectrum, where we observe two new structures and a possible third.

The J/ψφK candidates are fit bin-by-bin to extract the B signal yield, corrected by the relative efficiency (obtained from signal MC). Figure 1 (right) shows the Δm spectrum with two-signal-hypotheses fits , showing our observation of two new structures in the J/ψφ mass spectrum from exclusive B → J/ψφK decays at CMS with a significance above 5σ for each. The masses and widths of the two structures are measured as: m1 = 4148.0 ± 2.1(stat) ± 4.4(syst) MeV/c^2, Γ1 = 31.8 ± 10.3(stat) ± 24.1(syst) MeV/c^2; and m2 = 4314.5 ± 5.4(stat) ± 18.8(syst) MeV/c^2, Γ2 = 55.4 ± 28.4(stat) ± 35.5(syst) MeV/c^2.

The observation of two new structures in the J/Psi Phi spectrum has attracted much attention from the community. They are evidence of new exotic type of particle, as they can't be explained by the Quark Model, and is unique in that it is truly new and unexpected physics. This analysis will lead to years of followup work and subsequent analyses. The "third peak" will need more data in order to be resolved; however, the analysis becomes more difficult at higher instantaneous luminosities due to pileup effects and changing triggers. In order to study the properties of these new particles, a full-scale angular analysis will need to be performed; this will require new techniques to be developed in order to extract the needed information. Other channels could also be promising, and lead to other exotic mesons related to the new particles found here. Our group is poised to lead this effort, but it requires manpower and travel support to maintain our current role.

Scalar Meson Spectroscopy in CMS

Understanding the scalar meson spectrum in detail constitutes an important effort in studying the confinement theories as we understand them today. Current discussion about the scalar mesons is still at the "questioning the existence of the scalar nonet" level. There are many theories trying to explain their structures (e.g. diquark-antidiquark bound states or meson-meson bound states mixed with a scalar glueball) and CMS is the next-generation laboratory that could enable tests of this long-standing puzzle. Exploring the entire scalar spectrum would enable the study of the scalar meson structures in detail and of the possibility of new underlying symmetries both of which have the potential for new physics.

We propose to pursue several avenues in scalar meson spectroscopy. We have begun a study the scalar meson spectra in the excited meson decays in charmonium and bottomonium systems (e.g. $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$, $\Upsilon(3S) \rightarrow \Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$, $J/\psi \rightarrow \varphi\pi^+\pi^-$ and $J/\psi \rightarrow \varphi K^+K^-$); the σ meson search in $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ decay channel is documented in an internal CMS note[6] . We also plan to study the scalar meson spectra in three body decays of charm/strange mesons (e.g. $D^+ \rightarrow \pi^-\pi^+\pi^+$ and $D_s^+ \rightarrow \pi^-\pi^+\pi^+$) as well as study the scalar meson spectrum in radiative decays (e.g. $\varphi \rightarrow \pi\pi\gamma$).

Our first results in the σ meson search in $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ decay channel, where we find the variant mass and width to background subtracted data, considering two production models, are consistent with the CDF and BES results within systematic uncertainties. The mass of the σ meson is measured as m_σ= 569.0± 17.0(stat.)± 23.0(syst.) MeV/c^2 and its decay width as Γ_σ= 238.8± 66.9(stat.)± 71.0(syst.) MeV/c^2.

Search For Doubly Charmed Baryons in CMS

When the charmed baryon is added to the "uds" triplet system, the flavour symmetry of the baryon octet and decuplet is extended from SU(3) to SU(4). This would be a broken SU(4) symmetry due to the large mass of the charmed quark. There has been many models and predictions for the "ccq" states and the first experimental evidence for one of the six predicted doubly charmed baryon states emerged at a Fermilab experiment (SELEX), in which the Iowa-built M1 Spectrometer played a crucial role. CMS offers a feasible laboratory to study the doubly charmed baryons. Our proposed agenda is to initially search for the observation of the Ξ^+_{cc} through the decay channels $\Xi^+_{cc} \rightarrow \Lambda^+_c K^-\pi^+$ and $\Xi^+_{cc} \rightarrow pD^+K^-$. Further precision measurements and the exploration of other decay channels would follow the initial observations.

Observation of Ψ in CMS : Postdoc Alexi Mestvirishvilli has developed an analysis to search for Ψ to e+e- at CMS. This analysis is very challenging due to the low momenta of the decay products, and requires special triggers to collect the data. This study is ongoing, and results are expected in the coming year.

Multi-Jet Physics Program

CMS Dijet Analyses

The HCAL expertise of the Iowa group lends itself well to the search for New Physics in a jet-related channel. Multijet signatures are among the most promising for early discovery at the LHC; dijet resonance and angular ratio analyses can be sensitive to a range of models. In the past few years, we have built our physics group starting from jet-based signatures for new physics. Research Scientist Kai Yi and Sertac Ozturk (now an Assistant Professor at Tokat University, Turkey as well as an adjunct research scientist at Iowa) participated in the large-group effort of searching the dijet spectrum for mass resonances, resulting in the first Exotica group publication from CMS[7]. S. Ozturk worked on the resonance shape determination, and K. Yi worked on the significance calculation, where all fluctuations are evaluated for their statistical significance. Both then expanded their efforts to encompass new multijet signals, developing new analyses.

Paired Dijet Analysis

K. Yi has developed a four-jet analysis, searching the paired-dijet mass spectrum for evidence of new physics predicted by models for colorons and hyperpions. Colorons are predicted by models such as that of Dobrescu, Kong, and Mahbubani[8] where a pair of colorons is produced and then decays to quark-antiquark pairs. The signature is four well-separated jets, where the dijet mass of each pair matches to within 15% (3 σ). No significant excess was found in 2.2 fb^{-1} of data collected in 2011, and these results were approved for public presentation. Currently the analysis is being updated to examine the full 5 fb^{-1} dataset from 2011, which is in the CMS approval process and will lead to a journal publication[9]. No significant excess is observed, although there is an interesting bump at ~640 GeV, as can be seen in the plot in Figure 2(right). This small excess has attracted theoretical interest, as it could be evidence of a new particle that could also have an impact on the top asymmetry as measured at CDF. We are following this up with the 2012 data. This analysis is being done in collaboration with Fermilab and Rutgers, although we plan to add additional manpower to this effort in the coming months.

In addition to the paired dijet analysis, a followup analysis searching for pairs of top-antitop is also planned. Any real excess in the paired dijet mass distribution should also lead to an excess in the top-antitop spectrum, given the proposed model. This channel is being explored exclusively by Iowa, with Kai Yi guiding a second-year Iowa graduate student, Maksat Haytmuradov, in this analysis.

B-Tagged Dijet Resonance Analysis

Along with continuing to provide his expertise to the dijet mass resonance analysis, S. Ozturk has developed a b-tagged dijet resonance search which uses similar tools but extends the range to new signatures including Z' bosons, Axigluon/Coloron models, and Randall-Sundrum graviton production. The analysis strategy is to build from the untagged dijet analysis, adding in one and then two tagged jet requirements after choosing the optimal b-tagging strategy for this signature. Careful checks of 0-, 1- and 2-tagged jet events show good agreement between data and simulation. Currently we are estimating the resonance shape so that the spectrum can be evaluated for evidence of a signal. The current analysis is planned to be published by the end of 2012, and then work can begin to update it with the full 2012 dataset and explore enhancements and complementary signatures. As there are many possible models, some may require re-optimization of the selection or further evaluation.

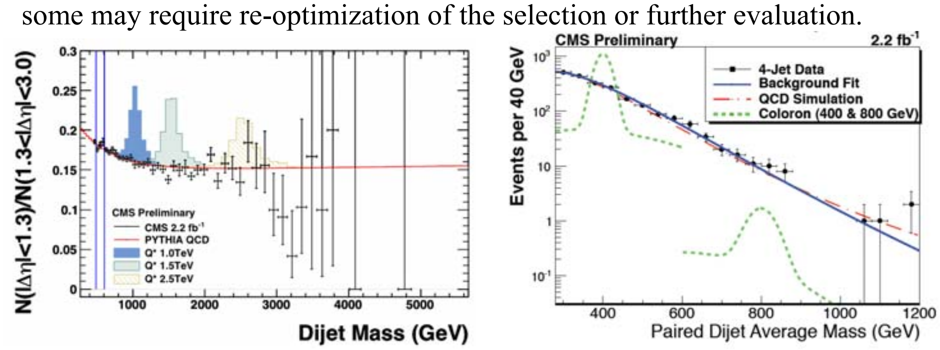

Figure 2 (left) : Dijet angular ratio from 2.2 fb^{-1} of data, compared to predictions for PYTHIA QCD and excited quark resonance models. (right) Paired Dijet Average Mass spectrum, showing data with background fit, and simulated coloron production superimposed.

Dijet Ratio Analysis

Research Scientist Taylan Yetkin and graduate student James Wetzel joined the CMS dijet centrality ratio analysis group in 2011. Certain models of new physics which manifest as a resonance decaying into two jets (pp → X → qq, qg, qq) are sensitive to angular relation between jets. The jets produced in Standard Model QCD processes are mostly at forward angles, whereas the models of new physics such as Excited Quarks, E6 Quarks, Axigluons, Colorons, Randall-Sundrum Gravitons, Heavy W/Z, and Strings involve resonances decaying into dijets that give isotropic angular distributions in the center of mass frame. As a result, the events from new physics processes have higher production rate with absolute pseudorapidity difference of jets ($|\Delta\eta|$) in the central region than by events predicted by QCD. The analysis exploits this fact by defining a dijet angular ratio. Events are selected with two energetic jets and categorized according to the absolute pseudorapidity difference $|\Delta\eta|$, with the number of events with $|\Delta\eta| < 1.3$ and $1.3|\Delta\eta|<3.0$ as the relevant comparison in the ratio.

The observed data are in good agreement with the Standard model prediction so limits may be set on the production of various models of physics beyond the standard model, as shown in Figure 2(left). With the 2.2 fb^{-1} of collected data, we excluded an excited quark of mass less than 3.20 TeV at 95% C.L., where the expected limit is 2.85 TeV. This limit can be compared to the published limits with 1 fb^{-1} from CMS[10] (2.68 TeV expected, 2.49 TeV observed) and ATLAS[11] (2.81 TeV expected, 2.99 TeV observed). This analysis resulted in a CMS Physics Analysis Summary (PAS)[12].

Search for Supersymmetry in Multi-jet plus Missing ET

Graduate student Elif Asli Albayrak and Research Scientist Taylan Yetkin have been key members for several years in the search for one of most likely channels to observe supersymmetry at CMS -- the multijet plus missing ET search for squark-gluino production. Strong production of squarks and gluinos has a high cross section at the LHC, and the least model-dependent method of searching is based on the final decay-chain products of these sparticles -- jets from the quarks and gluons and missing transverse energy from the lightest neutralino, which escapes detection.

This analysis was done by a large number of people working together, and so each institution contributes; the Iowa group contributed several key components of the analysis. Since the overwhelming background is from QCD events where the jets are mismeasured, estimating this background is essential. E. Albayrak developed a method to estimate this background by using the photon-jet sample in a pt-balance method, giving the jet energy response and resolution in back-to-back events. This data-driven measurement is then used to quantify the differences between data and simulation, including the non-Gaussian tails of the resolution, thus giving a more accurate and unbiased measurement of the QCD background. The work of E. Albayrak and T. Yetkin resulted in a journal publication[13], and also forms the basis of E. Albayrak's thesis.

Search for Heavy Majorana Neutrinos

Graduate student Warren Clarida recently completed a search for heavy Majorana neutrinos, forming the basis of his thesis (in progress) and resulting in a journal publication (recently submitted)[14] . In this model, the heavy neutrino is produced by a virtual W decay ($W^{+/-}$ to $Nl^{+/-}$) and the N is a Majorana particle, allowing for the decay to either sign of lepton, giving the possibility of a signature which is rare in the standard model -- two leptons with the same sign charge. Two possible decay channels were studied, both looking for same-sign dilepton plus dijet final states. W. Clarida's analysis focused on the dimuon final state, while also helping with a collaborating student from UC Riverside's search in the dielectron channel. As no excess was found in the 2011 data, limits were set on the production of heavy Majorana neutrinos;hese results are the first exclusion results from a direct search for masses above 90 GeV. The 2012 data run will result in more data than in 2011 and at a higher energy; therefore, we expect that these limits will be both improved and extended to a higher mass range in the coming year. We also hope to include additional channels in the study, particularly a search for signals with three leptons plus missing energy from the channel where the W boson decays leptonically, and a search in the electron-muon channel.

Energy Flow Measurement

Our group's expert knowledge of the HF detector and operating conditions gives us an advantage in forward physics analysis which provide important input for theoretical models of the underlying event structure. The energy flow, $dE/d\eta$, was studied by Research Scientist Taylan Yetkin and graduate student Sercan Sen at large pseudo-rapidities in proton-proton collisions at the LHC, for centre-of-mass energies of 0.9 and 7TeV in the pseudo-rapidity range $3.15 < |\eta| < 4.9$, for both minimum-bias events and events with at least two high-momentum jets. The data are compared to various pp Monte Carlo event generators whose theoretical models and input parameter values are sensitive to the energy-flow measurements. Inclusion of multiple- parton interactions in the Monte Carlo event generators is found to improve the description of the energy-flow measurements. Following the results published in this year[15], a second analysis is planned within the CMS FSQ (Forward and Small-x QCD) Physics group where we can redo the energy-flow measurement in the transverse, towards and away regions. Our group (Taylan Yetkin and Sercan Sen) will lead this effort, providing input for tuning of the event generators.

MCnet Project: Physics Simulations

The soft diffractive processes at the Large Hadron Collider, LHC, are important for understanding non-perturbative QCD effects and they also constitute a significant fraction of the total proton-proton (pp) cross-section. The measurement of the main characteristics of diffractive interactions is essential to improve our understanding of pp collisions. In order to observe diffractive events with the rapidity gap technique, we consider the pseudo-rapidity acceptance in the forward region of the ATLAS and CMS detectors at the Large Hadron Collider (LHC) and discuss the methods to select soft diffractive dissociation for pp collisions at $\sqrt{s} = 7$ TeV. Graduate student Sercan Sen is now analyzing the CMS data using this technique[16]. Within this project we also studied the energy-flow measurement in the transverse, towards and away regions; these physics simulations are done with the Rivet analysis tool.

Rapidity Gap Measurement

Currently, we are measuring the rapidity gap cross-section using CMS data (2010 data where the pileup is ~0)[17]; graduate student Sercan Sen is the contact person for the analysis, which will be approved for public presentation when the Minimum Bias Monte Carlo simulation is available in the next few months.

CDF Physics

Discovery of a Near-Threshold Structure in the $J/\psi\varphi$ channel from B^+ to $J/\psi\varphi K^+$ Decays

Our group has been a guest member of CDF for the past several years, since Jane Nachtman moved to Iowa from Fermilab. Then-postdoc Kai Yi originated our spectroscopy program beginning with the discovery of a near-threshold structure in the $J/\psi\varphi$ channel from B^+ to $J/\psi\varphi K^+$ decays[1]. Evidence for a new structure in the $J/\psi\varphi$ mass spectrum was found by our group, and was reported in 2009 with 2.7 fb^{-1} of data collected with the CDF detector at Fermilab. In 2010, the analysis was updated to include 5 $fb^{-1}$of data with the same selection criteria, yielding a structure with significance greater than 5 sigma, leading to the claim of discovery of a new particle, termed the Y(4140). In addition, evidence at 3.1σ for another structure in the J/Psi phi mass spectrum was found at 4280 MeV/c^2. This analysis is led by Dr. Kai Yi, and in July 2010, he presented the observation of the Y(4140) and evidence for Y(4280) at ICHEP. Dr. Yi subsequently joined CMS and began work on a confirmation analysis, as previously discussed.

Search for Diboson Production

Our current effort on CDF is a search for diboson production (γ/Z, where Z decays to b-bbar). Tim Harrington-Taber, a seventh-year graduate student, is finishing this analysis for his thesis work, and collaborates with Fermilab scientists on CDF. This analysis observes a cross section of 0.36 pb for this process, which has not previously been observed at the Tevatron.

Other work on CDF has included operation of the Silicon Vertex Detector until the Tevatron shutdown in late 2011. Currently we serve as godparents in the publication preparation process, and are otherwise concluding our CDF effort with Harrington-Taber's thesis, which will be completed this summer and will result in a journal publication.

HCAL OPERATIONS AND UPGRADES FOR THE ENERGY FRONTIER

HCAL Operations

The University of Iowa has played a crucial role in HCAL Operations, following the CMS policy of "build it, maintain it". Our group has had personnel stationed at CERN throughout the construction, installation, commissioning and now the operations and upgrade stages. Iowa engineer Ianos Schmidt has worked extensively with the CMS integration and infrastructure groups to supervise the HF cabling, radioactive source calibration system, low voltage distribution, cooling, gas, electrical, and detector safety systems. He has also performed the specification and installation of the final HF (+BSC) nitrogen distribution system and water cooling infrastructure. He continues to contribute to HCAL operations, lending his expertise to issues as they come up. Additionally, Ianos is working to facilitate the integration of TOTEM, CASTOR, BSC and BCM sub-systems/detectors that also occupy the CMS HF structures. The RADiation DAMage Monitoring (RADDAM) system was developed based on fiber transparency measurements to monitor radiation damage. This was tested with HCAL electronics during beam test activities; data agrees with previous transmission measurements. The RADDAM project is completely funded by the University of Iowa.

The Iowa group contributes to CMS operations, both at CERN and Fermilab. Research Scientist Taylan Yetkin, stationed at CERN, has worked as an HCAL Operations Coordinator and CMS field manager, and is currently co-leading the HCAL Integration group. Ianos Schmidt, also at CERN, is the HF Integration Engineer and CMS Forward Region Technical Coordinator. Alexei Mestvirishvili provides support as part of the HCAL Operations team. At Fermilab, Kai Yi has been the HCAL Prompt Analysis Coordinator and liaison between CMS Prompt Feedback Group (PFG) and HCAL PFG. Warren Clarida has been the HCAL Remote Operations Center (ROC) coordinator. Additionally, Iowa group members take many detector shifts both at CERN and the Fermilab ROC.

The University of Iowa is collaborating with The University of Kansas to develop, calibrate and commission two Zero Degree Calorimeter (ZDC) modules as part of CMS. The University of Iowa has provided mechanical engineering, construction, and calibration of the two sets of ZDC modules. Mechanical Design of the ZDC Tungsten Absorber, Frame Assembly, Quartz fiber assemblies, lightguides, and PMT mounts was completed at Iowa. Construction of the first ZDC (consisting of separate Hadronic and EM modules) was completed and assembled at CERN and test beam data were taken. Over the past few years, the ZDC remote lifting crane has been designed, validated, and built, with much of the effort coming from Iowa engineer Paul Debbins.

HCAL Upgrades For The Energy Frontier

The LHC will have a long shutdown period in 2013-2014 (referred to as LS1) to perform repairs and install new components to achieve higher center-of-mass energy collisions. The next long shutdown period (referred as LS2) is anticipated to start around 2020 with the main focus on improvements for higher luminosities.

During LS1, the CMS detector will undergo repairs and upgrades, as well as prepare for upgrades for LS2. The major improvement for the HCAL is the replacement of HF photomultipliers (PMT), in which our group continues to take a leading role, after leading the research and development to recognize the need for and propose the upgrade and select and characterize the PMT's. The LS2 activities are viewed as upgrades and our group is leading the HF multi-channel readout study for the new PMTs. We are also developing new methods and components for light collection from the endcap calorimeter (HE), where the current active detector components (scintillators) will not survive the high radiation environment of the LHC collisions that will be present beyond 2020.

Hadronic Forward (HF) Calorimeter Upgrade During the LHC Long Shutdown in 2013-2014
The HF calorimeters extend the pseudorapidity coverage up to $|\eta| = 5$, thus providing important information for forward jet tagging and missing transverse energy determination. The HF calorimeter plays a crucial role for the study of the Higgs boson and its couplings via observation and measurement of the vector boson fusion process, where jets are expected to be in the forward region. The missing transverse energy is a signature of many new physics models; its precise measurement is important for the CMS physics program.

Signal production in the HF calorimeter is based on Cherenkov mechanism: photons are produced in the plastic-clad quartz fibers by showering particles and measured by photo-multiplier tubes and front-end electronics. At the beam tests with production modules and later at the proton collisions in 2010 various noise sources were identified in the HF detector. These are termed ``PMT hits'' (muons interacting with the glass window and jacket of the PMT), late showering hadrons (charged particles interacting with the glass of the PMT), and scintillation light (produced in the material used in the light guide system inside readout boxes). Cosmic and beam halo also produce noise background.

We identified the detector components responsible for scintillation light (the highly reflective mirror material used for the light mixers) in the light guide mechanism and replaced them with non-scintillating material. However, the "anomalous PMT hit" noise remained, and was removed in data taken at low instantaneous luminosities by software algorithms based on event topology. With the increased luminosity the topological algorithms started to lose their efficiency; the most successful rejection algorithm was based on the early arrival time of the anomalous hits. However, this algorithm benefits from bunch spacing set at 50 ns thus far in LHC operations. When the LHC starts to operate with 25ns bunch spacing, timing rejection cannot be used. These difficulties will be solved with several changes in the detector during LS1 and LS2. During LS1, the current phototubes (Hamamatsu R7525) will be replaced with Hamamatsu R7600U-100-M4 multi-anode tubes. These new tubes have metal envelope and their window is thinner (< 1mm), which will significantly reduce the rate of anomalous signals by a factor of four as shown in collision and testbeam data. In addition, channel-to-channel variations were measured using the testbeam and ~12% variation was observed for two-channel readout. Further suppression is possible using the multi-anode nature of the PMTs. With additional readout channels, it is usually possible to identify single-particle anomalous signals and even to recover the response for the channel rather than rejecting the energy deposit entirely, as is done now. The algorithms to use multi-channel readout to suppress the background and recover the signal were developed and tested by our group using testbeam data collected at the CERN H2 facility. Our group provided a large portion of the effort (planning, operation, analysis, equipment) for the upgrade PMT selection, and has tested and characterized the ~2000 PMT's that will be installed in CMS during LS1. The necessary electronics for the additional channels are also part of this upgrade.

Another important capability developed for the upgrade will be a TDC capability in the ADC chip, allowing the determination of pulse arrival times and pulse widths for signals which are contained in a single charge-integration bucket, as must be the case for 25 ns operation. The pulse time measurement will also allow elimination of possible PMT noise hits which could fire the trigger earlier than the collision event, causing readout of empty events ("pre-firing"). Our group has been involved in the TDC development effort, through prototype construction for the testbeam and simulation studies. The design and TDC functionalities of QIE10 will be finalized after beam test studies with adapter cards for two- and four-channel readout options.

Phase II CMS R&D

Research and Development for Forward Calorimetry in CMS

By the end of the current decade several challenges will confront the CMS detector The integrated luminosity will have reached ~1000 fb^{-1}; the instantaneous luminosities will be ≥ 10^{34} cm^{-2} s^{-1} leading to pileup (> 20 overlapping interactions per bunch crossing). Ten years of effective operation of the current detector will have taken place. At the end of this era a long shutdown will allow modifications to the LHC to be made that will allow an increase in its instantaneous luminosity by an additional factor of ten. This High Luminosity LHC (HL-LHC) will provide an integrated luminosity of ~ 300fb^{-1} per year, leading to a total integrated luminosity of about 3000 fb^{-1}. Radiation damage to the calorimeters during this era will be far beyond the initial design specifications; it is thus highly likely that significant changes to the calorimeters will have to be made. Our basic working assumption is that we will want to maintain robust calorimetry coverage to $|\eta| < 5$ during HL-LHC operation. What form the calorimetry will take depends upon a combination of Monte Carlo studies and analysis of the data that CMS is presently accumulating and will depend upon whether we want to achieve excellent electromagnetic resolution or emphasize jet or Missing ET resolution by optimizing compensation in the combined ECAL-HCAL endcap, or both. For best EM resolution, one direction is to rebuild the EE in the same configuration as the present CMS endcap but with new radiation-hard crystals and photodetectors. For best overall jet energy and missing ET resolution, an endcap compensating calorimeter would require development of techniques to equalize electron and hadronic response by using detectors combining sensitivity to scintillation light and Cherenkov light emission and use of radiation hard photosensors. Our group has a history of calorimeter development and has a current program of proposed R&D for front end detector elements of the ECAL and HCAL to provide for either of the above options, including the following :

1. **Crystal R&D. (Caltech, Minnesota, Notre Dame, Iowa).** (a) studies of optical bleaching of PbWO4 crystals using infrared illumination – if successful, this may extend the life of the existing CMS ECAL significantly; (b) Rad Hard Crystal R&D - new crystals based on LSO and LYSO activated by Cerium – to replace elements in selected high radiation areas of the EE and transition regions between EE and HE; (c) Crystal fiber R&D (LYSO, LSO, YAG and LuAG) as a possible readout scenario for cells containing liquid scintillator or quartz tiles in the inner layers of the endcap hadron calorimeter.
2. **Hadron and Compensating Calorimetry R&D (Notre Dame, Virginia, Iowa, Fairfield, Minnesota)**. Sensing Cerenkov light and scintillation light to equilibrate e/h response exploiting the combined techniques under development including new sampling media – liquid scintillators, quartz tiles and capillaries, scintillation crystals and photosensor technologies. Beam testing is essential.

SUMMARY

In this report we have outlined the history of our group and our current trajectory in building a leading group in CMS physics analysis as well as the CMS HCAL present and future. We have an impressive record of training students and postdocs, publishing physics papers, and successful detector development.

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Final Report for TASK D: Theoretical Physics

I. INTRODUCTION

Task D, funded by the DOE since 1997, consists of two theorists, Y. Meurice and M.H. Reno. Our final report consists of a summary of our activities, primarily in the final renewal period of March 1, 2010 through April 30, 2013.

Y. Meurice develops new field theoretical methods which can be used in situations where perturbative methods are inaccurate or fail. This involves improved perturbative methods obtained by cutting off the large field configurations in the path integral, the $1/N$ expansion, semi-analytical calculations of renormalization group flows and Monte-Carlo simulations in lattice gauge theory. The long term goal is to bring higher standards of accuracy in quantum field theory and to be able to make predictions that can be compared with experiments which emphasize precision ($g-2$, hadronic width of the Z, etc...) as well as to understand the question of conformal windows in gauge theories.

M. H. Reno's research is in the area of elementary particle phenomenology, focusing on neutrino phenomenology and more recently particle dark matter. Her research has included work on standard and non-standard model extrapolations of the neutrino-nucleon cross section, in particular target mass corrections and an evaluation of the transition through heavy quark thresholds. In general, the cross sections are relevant to underground, underwater and under ice detectors as well as air shower and radio Cherenkov detectors. Part of Reno's focus has been on lepton electromagnetic energy loss, an important ingredient in the analysis to interpret underground events induced by muon neutrino interactions. Particle physics interactions are a critical element of the evaluation of atmospheric neutrino and muon fluxes. Reno has contributed in this area, and she has applied some of the same principles to high energy neutrino production in a class of sources. She has recently included particle dark matter physics in her research efforts.

In the next two sections, we summarize our main results. In Section IV, we include a list of publications and talks. Section V lists the students who were supported in part by the DOE grant during the final renewal period.

II. LATTICE GAUGE THEORY - MEURICE

Overview

Several decades of joint theoretical and experimental effort have established that the Standard Model is an amazingly good description of the fundamental interactions up to the highest energies probed at collider experiments. The most recent LHC results have provided evidence of a Higgs particle with a mass near 126 GeV, well inside the window 55 GeV $\leq M_H \leq$ 135 GeV predicted from Standard Model radiative corrections and precision physics calculations made years before the LHC results [1]. As there are number of theoretical reasons to doubt of the existence of fundamental scalar particles, future analysis will scrutinize the compatibility of the observations in various channels with the Standard Model predictions. However, at this point, there are no clear indications for new particles, new scales or new interactions beyond the Standard Model.

This means that lattice gauge theory will play a major role in finding possible discrepancies with the Standard Model in weak decays and in proposing alternative to the standard Higgs mechanism. In the next few years, the main priority of my research group will be to use and develop nonperturbative methods to deal with strong interactions. In the past years, we have developed new methods to improve perturbative and renormalization group approaches of lattice field theory and worked on numerical simulations for QCD or QCD-like lattice gauge theory models.

A possible alternative to the mass generation by a fundamental scalar particle is to have a composite Higgs made out of fermions interacting strongly via new gauge interactions. This possibility is often referred to as Technicolor and phenomenologists favor scenarios with a slowly evolving ("walking") gauge coupling constant. This typically occurs in situations that can be described as "near conformal". In this regime, understanding the strong dynamics is a difficult nonperturbative problem that needs to be properly handled before trying to do realistic model building. Small discrepancies with the Standard model predictions for weak decays of hadrons requires precise lattice gauge QCD calculations. Heavy flavor physics will provide very interesting possibilities in the near future, especially at LHCb.

Our theoretical effort is divided in three parts: A) complex RG flows and the conformal window, B) B-physics, C) new methods in Lattice Field Theory. The technical aspects for each of these three directions will be discussed below. The goals of our research are clearly in line with the main objectives of the Theoretical High Energy Physics program of the DOE. Our recent work on B-physics has a direct impact for experimentalists working on the Intensity Frontier. Our work on the conformal window is intended to have a significant impact on the experimental program in Energy Frontier.

I have supervised six graduate students during the last three years: Daping Du (Ph. D. 2011), Yuzhi Liu (Ph. D. 2013), Alan Denbleyker (Ph. D. expected in 2013), Haiyuan Zou (Ph. D. expected in 2014) and Judah Unmuth-Yockey (Ph. D. expected in 2016) and Zech Gelzer (Ph. D. expected in 2017). More details are provided in a separate section. My research group uses Linux clusters, some built and operated by the group itself and supported by the grant or the University of Iowa, and others at Fermilab and NERSC.

Service to the physics community

Thanks to the support, I organized four workshops (at INT (Seattle), Aspen, and KITPC (Beijing),"Lattice Gauge Theory in the LHC Era" for summer 2013 at Aspen. A proposal for KITP for 2015 has been selected. I have been on the Advisory Board of Journal of Physics A since 2001. I was a Guest Editor for Philosophical Transactions of the Royal Society A in 2010-2011 and contributed a Theme Issue in 2011. I referee papers frequently for many journals. I have worked on increasing the participation of junior scientist in conferences and workshops and have recently obtained a grant from ICAM for this purpose.

Technical results

A. Complex RG flows and the conformal window

In recent years, there has been an intense activity in the lattice community to find viable alternatives to the standard Higgs mechanism. The possibility of having a strongly coupled and composite Higgs sector has motivated searches for nontrivial infrared fixed points in asymptotically free gauge theories. The location of the conformal windows, the region in parameter space where a nontrivial infra-red fixed point exists, for several families of models have triggered heated discussions. Different numerical and analytical techniques have been applied to QCD-like models with large number of fermion flavors [2–7] or with fermions in higher representations [8–13]. See also [14–16] for recent reviews of results and expectations.

A situation of particular interest is when the β function for a new hypothetical gauge coupling approaches zero from below and starts "walking". This near conformal situation can be obtained in some examples [17] by varying a parameter in such a way that two RG fixed points coalesce and disappear in the complex plane. This motivated us to study extensions of the Renormalization Group (RG) flows in the complex coupling plane [18–20]. In all examples considered, we found that the Fisher's zeros act as "gates" for the RG flows ending at the strongly coupled fixed point. The Fisher's zeros are the zeros of the partition function in the complex inverse coupling or inverse temperature plane (later, we use the "β-plane" terminology). This is a complex extension of the general picture of confinement proposed by Tomboulis [21]. In the case where a phase transition is present, the scaling properties of the zeros [22–27] allow us to distinguish between a first and second order phase transition.

Complex Renormalization Group Flows in Spin Models

Calculations of RG flows and discrete β functions in lattice gauge theory are notoriously difficult. One of the main question asked is how many flavors does it take to destroy the confining properties of the theory. For gauge theories, the absence of long-range order (no massless gluons) is associated with confinement. The absence of long-range order also characterizes the 2-dimensional $O(N)$ sigma models with $N \leq 3$. By using some approximations, it is possible to calculate complex RG flows and Fisher's zeros much more easily than for gauge theories.

In [20], we were able to monitor RG fixed points disappearing in the complex inverse temperature (β) plane using the two-lattice matching procedure [28, 29] for Dyson's hierarchical model [30, 31] with an Ising measure. In this model, the local potential approximation is exact and RG flows can be calculated numerically with good accuracy [32]. The model has a free parameter that plays the role of the dimension and can be tuned continuously. For $D = 3$, the model has a nontrivial Wilson-Fisher fixed point. As we lower D continuously, the fixed point on the real axis moves to the right and eventualy disappears at infinity for $D = 2$ in agreement with rigorous results [32].

An important feature that can be observed is that the RG flows approximately follow the Fisher zeros along the separatrice between different basins of attraction. More specifically, in one discrete step, the RG flows approximately go from the zeros at one given number of lattice sites to the zeros for a smaller number of sites as obtained after block spinning. This example shows that the global properties of the RG flows (difficult to calculate) can be inferred from the location of the Fisher's zeros at successive volumes (easier to calculate).

Similar observations were made for the $2D$ $O(N)$ non-linear sigma models in the large-N limit. In [19], we constructed the Riemann sheet structure and singular points of the finite lattice size L mappings between the mass gap and the 't Hooft coupling. We argued that the Fisher's zeros appear on "strings" ending approximately at the singular points. We compared finite volume complex flows obtained from the rescaling of the ultraviolet cutoff in the gap equation and from the two lattice matching. In both cases, the flows are channelled through the singular points and end at the strong coupling fixed points, however strong scheme dependence appear on the ultraviolet side.

At Lattice 2011, Yuzhi Liu discussed the possibility of constructing a continuous beta function from the discrete one by using functional conjugation methods described in Gell-Mann and Low. He presented results showing that zeros of the discrete β function can disappear when the volume is increased and stressed the importance of nonlinear effects in scaling functions. These findings will be relevant to recognize pitfalls in the search of nontrivial fixed points in multiflavor lattice gauge theory models.

Fisher's zeros from density of states in pure gauge models

We have used the density of states $n(S)$, the exponential of the entropy which describes the relative number of configurations with a given action S, to analyze the Fisher's zeros of lattice gauge models. The pure-gauge partition function can be written as the Laplace transform of the density of states. which allows us to calculate Z for complex values of β.

In the case of $D = 4$ pure gauge $SU(2)$, numerical results were checked with existing expansions [35], and it was found that the zeros stay away form the real axis as the 4-volume increases [18]. In the case of $D = 4$ pure gauge $U(1)$ theory [36], we used the multi-canonical algorithm developed by Berg and Bazavov [37] to construct the density of states. For small volumes, we were able to locate the lowest zeros with a precision of order 10^{-5}. The imaginary part of the zeros scales like $L^{-3.07}$, or $\nu = 0.326$ in the apparently consistent second-order phase transition hypothesis. However the zeros from higher volumes show that the scaling is "rolling" and ν is decreasing with volumes This is consistent with a study based on Binder cumulants [38]. Lower statistics data including volumes up to 20^4 shows the compatibility with the first order scenario [36], but this remains to be confirmed with higher statistics.

Our effort to study the Fisher's zeros for $SU(3)$ with N_f flavor in collaboration with Don Sinclair has been supported by a one-year grant and will be reported in the final report for this separate grant.

B. B-physics.

The Fermilab Theory Group has a very active program of research in lattice-QCD calculations, involving Paul Mackenzie, Andreas Kronfeld and, Ruth Van de Water. As flavor physics provides many ways to search for new physics, they have been able to involve two of our well-prepared graduate students in 1-year projects with URA support. In addition, our experimental group has extensive experience in B-physics and helped us understand the experimental needs.

Semileptonic form factors for $B_s^0 \to \mu^+\mu^-$

In 2010, my student Daping Du started a project in Lattice QCD with Andreas Kronfeld and other members of the Fermilab Lattice-MILC collaboration . His plan was to extract, using both lattice QCD calculations and upcoming experimental results, the branching ratio for the decay $B_s \to \mu^+\mu^-$ which is sensitive to the physics beyond the Standard Model(SM). Based on the method suggested by Fleischer, this branching ratio can be approached from other cleaner and reliable channels like $B_d^0 \to K^+\pi^-$ etc by determining the fragmentation functions f_d/f_s with a satisfactory uncertainty level. The project reduced the error from the theoretical calculation. It also reinforced the collaboration between the theoretical and experimental groups in High Energy Physics at University of Iowa.

In recent years, increasing interest has been placed on the rare decay $B_s^0 \to \mu^+\mu^-$ where the Penguin and Box topologies dominate due to the GIM mechanism, and it will potentially open a window for testing of the Standard Model and detecting the signals of the

New Physics. The branching ratio of the process predicted by the Standard Model with parameters determined from the lattice QCD calculations is about $(3.6 \pm 0.4) \times 10^{-9}$ while the upper bound from the CDF and DØ collaboration was around 4×10^{-8}. The most recent measurement at LHCb is $2.9 \pm 0.7 \times 10^{-9}$ very close to the lattice result.

At LHCb, the branching ratio is obtained by using comparison with other normalization channels like $B_u^+ \to J/\psi K^+$ or $B_d^0 \to K^+\pi^-$ in the following manner:

$$BR(B_s^0 \to \mu^+\mu^-) = BR(B_q \to X)\frac{f_q}{f_d}\frac{\epsilon_X}{\epsilon_{\mu\mu}}\frac{N_{\mu\mu}}{N_X}$$

where the efficiencies ϵ and count numbers N come from experimental measurements. Significant uncertainty comes from from the ratio f_q/f_s for which a precise estimate is yet to be seen. As a result, the fragmentation ratio can be expressed explicitly by

$$\frac{f_d}{f_s} = 12.88\frac{\tau_{B_s}}{\tau_{B_d}}\frac{\epsilon_{D_s\pi}}{\epsilon_{D_dK}}\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\frac{a_1(D\pi)}{a_1(DK)}/\frac{N_{D_s\pi}}{N_{D_d\pi}} \tag{1}$$

and we focused on the extraction of the form factors ratio $F_0^{(s)}(m_\pi^2)/F_0^{(d)}(m_K^2)$ which contributes to the major uncertainty in $BR(\bar{B}_s^0 \to D_s^+\pi^-)/BR(\bar{B}_d^0 \to D^+K^-)$. In 2011, Daping Du worked on these form factors at Fermilab. A URA supported this collaboration with Andreas Kronfeld, which has been a total success. Daping blossomed as a physicist while at Fermilab and became postdoc at the University of Illinois in Urbana. Using MILC ensembles of gauge configurations with 2+1 flavors of sea quarks he calculated the ratio :

$$f_0^{(s)}(m_\pi^2)/f_0^{(d)}(m_K^2) = 1.046(44)_{\text{stat.}}(15)_{\text{syst.}} \tag{2}$$

This ratio of semileptonic form factors is defined precisely in [40]. Recent preprints [41, 42] show that it is now becoming the standard estimate.

This work also led to a second, serendipitous paper on a hint of new physics. The contribution of scalar form factors to the semileptonic decay $B \to D\tau\nu$ in the standard and 2-Higgs models provide a possible interpretation for the recent discrepancy found at BaBar. More detail can be found in a paper that has just been published as a highlighted PRL [43].

Form factors for $B_s \to K\mu\nu$

In 2012-2013, my student Yuzhi Liu has worked on the $\bar{B}_s \to K\mu\nu$ decay mode. He plans to predict the shape and normalization before the currently running LHCb experiment provides data and estimate the CKM matrix element $|V_{ub}|$. He has been able to calculate correlations between weak currents and meson interpolation operators using various statistical ensembles generated by the Fermilab lattice group. Recent calculations of the 2 and 3 point functions together with chiral extrapolations will unable him to complete the calculation of the matrix elements for the transition B_s to Kaon necessary to estimate the CKM element V_{ub} using measurements that will be conducted at LHCb. As noted in the ORKA proposal, more precise knowledge of $|Vub|$ is essential for rare kaon experiments, like ORKA and those envisioned with Project X, to probe physics beyond the Standard Model. Fermilab/MILC will provide the necessary computing resources for this project.

C. New methods in Lattice Field Theory

Fast progress in CPUs and GPUs have improved the accuracy of Monte Carlo simulations, but, ultimately, we need to find more analytical methods to understand the continuum limit and the infinite volume limit of lattice models. It is clear that it is a mature field and that the unsolved problems are very difficult. Usually, one needs to start with models that are less complicated than lattice gauge theory such as quantum mechanics and nonlinear sigma models and increase the dimension. We have been working in two directions: 1) Improving Feynman diagrams methods (control of the large field contributions in the path integral), 2) Improving Renormalization Group methods (removing the "walls" in blocking procedures).

Improved perturbative methods

Perturbation theory has played an essential role in developing and establishing the Standard Model. The renormalizability of the theory guarantees that we can calculate the radiative corrections at any order. On the other hand, a generalization of Dyson's argument suggests that the perturbative series are divergent and one needs to truncate the series in order to get a finite answer. The factorial growth of perturbative series is related to configurations with arbitrary large fields [44]. A large field cutoff provides converging series with exponentially small errors for quantum mechanics problems [45, 46]. In lattice models with compact groups, the factorial growth can be circumvented by maintaining a finite range of integration [47]. In this framework, the nonperturbative part of simple quantities in gauge models and quantum mechanics can be estimated [48]. This question has also been discussed in the large-N limit [49] and an apparent paradox related to the gauge models dual to de Sitter spaces clarified [50].

Recently the Amherst group has proposed a sequence of approximants to tame the large field contributions while keeping Wick theorem and Feynman rules [51]. At Lattice 2011, my student Haiyuan Zou [52] compared the efficiency of their method with the simple large field cutoff method for integrals and quantum mechanical problems. He is now working on improving perturbative methods for non-linear sigma models and $U(1)$ lattice gauge theory. He has found that the boundary conditions (b.c.) for the $D = 1$ $O(2)$ nonlinear sigma model have a strong effect on the nonperturbative part of the average energy E defined as $|(E-E_{PT})/E|$ with E_{PT} the perturbative series truncated at the optimal order. This quantity is proportional to $e^{-2\beta}$ for open b.c. and to $e^{-\beta E_v}$ for periodic b.c., where E_v is the energy of the periodic solution of the classical equation of motion with winding number 1. He is now working on the same problem in $D = 2$ where the evaluation of perturbative expansions is more complicated. Recent reformulations using the tensor RG (see below) offers a promising way to implement the perturbative expansions. He then plans to follow a similar procedure for $U(1)$ lattice gauge theory in $D = 3$ and $D = 4$, where the Feynman rules are very similar after gauge-fixing. Later, the non-abelian case where stochastic perturbation theory results are available, will be considered.

Improved RG methods

One difficult problem in the RG approach is to improve local potential approximations [32]. Monte Carlo Renormalization Group has been applied to multi flavors systems by using the two lattice matching technique [3, 7]. Recently we have tested the matching using the Migdal-Kadanoff approximation and found discrepancies. We plan to test if the improvement proposed in by Tomboulis improves this situation.

The tensor network formulation [53] provides surprisingly efficient ways to perform coarse graining. Very recently, we have worked with Tao Xiang's group to extend successfully their accurate method to $O(2)$ models. We have also calculated the tensors for $O(3)$ spin models and $U(1)$ gauge models, but the numerical implementation remains to be done. We plan to apply this promising method to other lattice gauge theory models. In short we start from an exact tensor form for the partition function. For the Ising model

$$Z = (\cosh(\beta))^{2V} \mathrm{Tr} \prod_i T^{(i)}_{xx'yy'} \ . \tag{3}$$

It reproduces the closed paths of the HT expansion. It has been observed that [53, 54] TRG blocking separates the degrees of freedom inside the block which are integrated over, from those kept to communicate with the neighboring blocks and provides *exact* blocking formulas.

For the Ising model on square and cubic lattices, truncation method (HOSVD) sharply singles out a surprisingly small subspace of dimension two. In the two states limit, the transformation can be handled analytically yielding a value 0.964 for the critical exponent ν much closer to the exact value 1 than 1.338 obtained in Migdal-Kadanoff approximations. Alternative blocking procedures that preserve the isotropy can improve the accuracy to $\nu = 0.987$ and 0.993 respectively. Applications to other classical lattice models are possible, including models with fermions. TRG could become a competitor for the Monte Carlo method suitable to calculate accurately critical exponents, take continuum limits and study near-conformal systems in large volumes. In a very recent preprint arXiv:1307.6543 we wrote explicit formulas for the blockings for most lattice models. Successful numerical implementations in situations with sign problems give very promising results that will be reported in subsequent publications.

III. PARTICLE PHENOMENOLOGY - RENO

Overview and Personnel

Reno's research in the final renewal period has been on topics in neutrino physics and on indirect detection of dark matter. Research in the past several years has been performed with Professor Ina Sarcevic (University of Arizona), Professor Graciela Gelmini (UCLA), Professor Rikard Enberg (Uppsala University, Sweden), University of Arizona postdoc Dr. Tolga Guver (now at Sabanci University, Turkey), my former students Alexander Bulmahn (PhD 2010, currently lecturer at University of Montana) and Yu Seon Jeong (PhD 2011, currently a postdoc at Yonsei University in Korea), and Arif Erkoca (formerly a graduate student at Arizona, PhD 2010). A University of Iowa graduate student, Minh Vu Luu, has joined my effort in the past year.

Technical report of recent results

High energy neutrinos

Neutrinos, as particles without electromagnetic and strong interaction charges, are messengers that point back to cosmic sources and to the interiors of astrophysical sources [55]. With observations of cosmic rays up to energies of order 10^{10} GeV [56], one expects to observe ultrahigh energy neutrinos from the astrophysical environments that produce these cosmic rays [57]. Furthermore, a Greisen-Zatsepin-Kuzmin cosmogenic flux of neutrinos from cosmic ray interactions with the cosmic background radiation is expected at some level. The IceCube detector [58] is designed to observe astrophysical neutrinos, and a number of other detectors like the Auger array [56] have the potential to observe neutrino signals as well.

A key element in the interpretation of neutrino fluxes is the neutrino cross section with matter for a range of energies. In evaluating the weak interaction cross sections, the W and Z boson propagators set the scale of the momentum transfer at high energies to $Q^2 \sim M_{W,Z}^2$, which in turn sets the scale of the parton momentum fraction to $x \sim M_{W,Z}^2/M_N E_\nu$ where M_N is the nucleon mass. The cross section for high energy neutrino-nucleon scattering requires parton distribution functions (PDFs) at small x and $Q^2 \sim M_{W,Z}^2$. With Quigg, Sarcevic and Gandhi, we evaluated the ultrahigh energy neutrino-nucleon cross section with the then state-of-the-art PDFs measured at HERA [59], updating earlier evaluations of the neutrino cross section. Since then, there have been a number of re-evaluations of the cross section [60–64] including the use of updated HERA PDFs with NLO contributions, discussions of the effect of different flavor number schemes and alternatives to straightforward extrapolations of the conventional DGLAP evolution of the PDFs, as in e.g., Refs. [65, 66]. Our research during the past four years has contributed to the refinement of UHE neutrino-nucleon cross section calculations.

As part of Yu Seon Jeong's PhD thesis research, we evaluated the implications at UHE of the treatment of charm and bottom quarks as "heavy flavors" throughout the whole energy range versus their treatment as "light flavors" when $Q \gg m_{c,b}$. At the highest energies considered, $E_\nu = 10^{12}$ GeV, the flavor scheme dependence amounts to discrepancies in the neutrino-nucleon cross section of about 15%. This is a relatively small effect compared to uncertainties associated with the extrapolations of the PDFs to very small parton x at ultrahigh energies. Our work on the flavor scheme dependence at UHE appears in Ref. [60]. In a second paper with Yu Seon Jeong [67], we also looked at the lower energies, $E_\nu \sim$ a few GeV to 10 TeV, in tau neutrino charged current interactions with nucleons. We evaluated heavy quark effects and the additional consequences of target mass corrections, low Q extrapolations of structure functions and the kinematic corrections due to the tau lepton mass. This built on earlier work with collaborators on the impact of target mass corrections, with NLO QCD, on the muon neutrino and tau neutrino cross sections with nucleons [68, 69]. It also made use of my earlier work on the translation of low Q extrapolations of the electroweak structure functions to weak interaction structure functions [70].

With Ina Sarcevic, and also with Yu Seon Jeong as part of her PhD thesis research, our paper on radio Cherenkov signals of neutrino interactions in the Moon [71] was motivated by an effort to constrain the ultrahigh energy (UHE) neutrino cross section without input from the theory of weak interactions and PDFs. Here, the neutrino-nucleon cross section is taken as a parameter in the evaluation of the interaction rate of cosmogenic neutrinos in the Moon.

Neutrino interactions in materials produce a charge excess which can travel faster than the speed of light in the material. This effect, called the Askaryan effect, has been measured in laboratory experiments using electromagnetic showers generated by photons at SLAC

[72]. With a scientific goal of measuring or constraining the neutrino flux associated with the cosmic ray GZK cutoff, there are searches for radio Cherenkov signals from neutrino interactions in the Antarctic ice [73] and from neutrino interactions in the lunar regolith, e.g., in Refs. [74–76]. As part of the University of Iowa team's limits using the Very Large Telescope Array, Gayley, Mutel and Jaeger developed a semi-analytical evaluation of the effective aperture for neutrino-induced radio Cherenkov signals from the Moon [77]. This provides a starting point for examining the impact of large uncertainties in the ultrahigh energy neutrino nucleon cross section.

To evaluate the neutrino signals from the isotropic flux of neutrinos coming from cosmic ray interactions with the microwave background [78], we used the approximate analytic expression of Gayley et al. [77] to evaluate the contributions to a radio Cherenkov signal from neutrinos which pass through most of the Moon and interact near the surface, producing an "upward" shower and from neutrinos which produce "downward" showers in the face of the Moon pointed towards Earth. The key element with the downward showers is that there are various angles for the radio signal (Cherenkov angle, refraction angle and Cherenkov cone size) plus corrections coming from the fact that the surface of the Moon is uneven. We extended the Gayley et al. analytic results from Ref. [77] to include cosmic ray production of radio Cherenkov signals (all downward). The cosmic ray calculation involves accounting for attenuation of cosmic rays in the lunar regolith. Modifications of the analytic results were made to allow the neutrino cross section to be much lower and much higher than the DGLAP evolved PDF-based standard model predictions. When the neutrino cross section with nucleons is strongly enhanced, as in for example, extra dimensional models in which mini-black holes can be produced (see, e.g., Ref. [79]), neutrino attenuation in the lunar regolith is similar to that of cosmic rays.

Our conclusions in Ref. [71] include the fact that radio Cherenkov signals of cosmic ray interactions in the lunar regolith dominate signals from cosmogenic fluxes of neutrinos if the neutrino-nucleon cross section is roughly the standard model value. If the neutrino nucleon cross section is much larger than the standard model value, cosmogenic neutrino rates are larger than the cosmic ray background in the lunar radio Cherenkov signal. For relatively large isotropic neutrino fluxes which scale as $A\cdot E_\nu^{-2}$, one has the potential to use the absence of lunar radio Cherenkov signals to constrain A as a function of $S=\sigma_{\nu N}/\sigma_{\nu N}^{SM}$, the ratio of the neutrino cross section to the standard model cross section, in an interesting portion of parameter space.

Muon and tau electromagnetic energy loss

Charged lepton energy loss through electromagnetic interactions in materials is an important ingredient in the analysis of underground/underwater signals of neutrino charged current interactions and the backgrounds from atmospheric muons. My graduate student Alex Bulmahn and I have reevaluated the e^+e^- pair production differential cross section for muon interactions with atoms in materials like rock or ice [80]. Electron-positron pair production is the most frequent interaction for muons in transit through material, although it is dominated by low energy losses. Earlier evaluations, e.g., by Kel'ner in Ref. [81] and subsequent authors, relied on the static nucleus approximation. We include recoil kinematics (see also Akhundov, Bardin and Shumeiko [82]) for elastic scattering, as well as inelastic scattering. Our results for electron positron pair production agree well with the commonly used expression of Kokoulin and Petrukhin (ICRC Conf. Proc. 1971) for the energy loss parameter β and for the differential cross section, mainly because the cross section is dominated by very low momentum transfers to the target. Our evaluation is applicable to tau antitau pair production as well as electron positron pairs. For these massive leptons, the momentum transfer is much larger, so inelastic contributions, negligible for electron positron pairs, are important.

As part of his PhD thesis research, Alex Bulmahn and I evaluated the flux of high energy electrons and taus in underground detectors [83]. We looked at the production of electrons and positrons with energies larger than 10-100 GeV by high energy atmospheric muons in IceCube. The high energy electron flux probes the high energy tail of the electron energy distribution in the muon production of electron pairs, a kinematic region where the full calculation of the differential cross section is most important and where the prompt muon flux may be more important than the conventional atmospheric muon flux.

An interesting application of the formalism is to tau pair production. We evaluated the PeV flux of taus from prompt and conventional atmospheric muons, and from atmospheric tau neutrino conversion to taus for IceCube[83]. A different geometry for tau production is seen with the HAWC telescope. While its main science objective is to study the origin of cosmic rays through TeV gamma ray showers and to survey gamma ray sources, HAWC's location allows an opportunity to potentially observe tau neutrinos. The tau neutrinos, in transit through the mountain, could convert to taus. With sufficiently high energies, taus could exit the mountain before decaying. For appropriate angles, the decay products could be detected in the water cherenkov tanks. We found that atmospheric tau neutrinos dominate the tau rate for a detector like HAWC, however at energies above $E_\tau \simeq 10^6$ GeV, the contributions of taus from atmospheric muons provides about 20-30% of the total tau flux.

Even though tau pair production by muons is low, their decay to tau neutrinos is a potential background to extragalactic tau neutrinos. We evaluated the secondary flux of tau neutrinos from $\mu A \to \mu\tau\bar{\tau}X \to \nu_\tau\bar{\nu}_\tau X'$ [84]. We found that the tau neutrino flux from muon production of tau pairs is small compared to the prompt flux of tau neutrinos from D_s production for the range of energies considered: $10^2 - 10^6$ GeV.

Particle dark matter

The particle nature of dark matter is one of the outstanding problems in particle physics and astrophysics. Dark matter, comprising 25% of the matter density in the Universe, may have interesting particle properties that have implications for astrophysical objects. Ultimately, collider physics experiments together with astrophysical constraints and direct detection of dark matter interactions with ordinary matter will pin down the particle nature of dark matter [85]. Our recent work on indirect detection of dark matter has evolved into several projects, with proposed research related to direct detection and constraints from indirect detection and collider experiments.

We have considered indirect detection constraints on dark matter in scenarios with dark matter annihilation resulting in neutrino signals in neutrino telescopes, as described in a series of papers [86–88]. The first paper, in collaboration with Sarcevic and Erkoca, focused on dark matter annihilations in the Earth, Sun and Galactic center [86]. The emphasis of this paper is on the neutrino induced muon spectrum, and the importance of the muon energy distribution and energy loss in matter for large underground detectors like IceCube.

In two subsequent papers, we further explored probes of dark matter from dark matter annihilation near the Galactic center [87, 88]. In particular, in Ref. [87] with Sarcevic, Erkoca and Gelmini, we investigated upward muon, contained muons and shower signals from annihilation through several channels for two different dark matter profiles. The shape of the signal muon or shower distributions from annihilating dark matter was contrasted with the atmospheric neutrino background contribution.

The positron excess in the measurements of cosmic rays by the PAMELA experiment [89] stimulated considerable theoretical activity on dark matter models. In Ref. [88], Sarcevic, Erkoca and I chose a few specific models which could account for the PAMELA excesses and were also consistent with HESS and FERMI/LAT results [90]. We considered choices for dark matter as a gravitino, a Kaluza-Klein particle, and a particle in a leptophilic model in annihilation and decay scenarios. We evaluated the optimal observational cone half-angles with respect to the Galactic center, as a function of models with neutrinos from either annihilation or decay, in which the dark matter signal could best stand out from atmospheric neutrino backgrounds.

Direct detection of dark matter is primarily sought in experiments which are sensitive to the low energy interactions with the ambient dark matter, since near Earth, dark matter velocities are on the order of $v \sim 10^{-3}\ c$. With my former student Y. S. Jeong and with C. S. Kim, we have discussed in Ref. [91] an alternate and more exotic possibility for direct detection: high energy dark matter interaction with nucleons. Direct interaction signatures of sub-GeV dark matter interactions, in which the dark matter is produced in neutrino beams, is discussed by deNiverville, McKeen and Ritz in Ref. [92].

We evaluated cross sections for $E > 10^3$ GeV. Using low energy direct detection constraints on the spin-independent (SI) and spin-dependent (SD) dark matter-nucleon cross section, we have evaluated the possibility that, in the event there is a source of high energy Majorana particle dark matter, the dark matter interactions with nucleons could mimic neutrino neutral current interactions. An intriguing case is for a ~ 10 GeV dark matter particle which interacts with standard model particles via a Z' with a mass of order 15 GeV and suppressed couplings. This scenario can accommodate the dark matter density in the universe and collider constraints, and it lies in a potentially interesting mass window for direct detection experiments.

Finally, we have considered dark matter in the astrophysical context, dark matter accumulation in neutron stars, with Sarcevic, Erkoca and Guver [93]. McDermott, Yu and Zurek in Ref. [94] put constraints on "asymmetric" dark matter from neutron stars. Asymmetric in this context means the dark matter does not self-annihilate. The constraint explored in their paper is that the dark matter, in this case, scalar dark matter, can not accumulate so much in the core of the neutron star so as to collapse the neutron star into a black hole. The existence of neutron stars restricts properties of asymmetric scalar dark matter.

With Guver, Erkoca and Sarcevic, we extended the work of McDermott et al. [94] and of Kouvaris and Tinyakov [95, 96], where we consider both fermionic and scalar dark matter (χ), and we include the effects of self-capture ($\sigma_{\chi\chi}$) [93]. For fermionic dark matter, we find that for $M_{DM} > 100$ GeV, the fermion Chandrasekhar limit is less than the number of fermions required for the fermionic dark matter to be relativistic. Thus for $M_{DM} > 100$ GeV, the minimum number of fermions is governed by the relativistic constraint rather than the Chandrasekhar constraint if a black hole is to be formed.

For bosons, there is the added element that bosons can form a Bose Einstein condensate (BEC) in the core of the neutron star. Once the BEC is formed, self capture is not an important feature because the geometric cross section for the dark matter in the core is so small. For small dark-matter nucleon cross sections, and large dark matter self-interactions, the self interaction can become important. We have evaluated the time dependent self capture rate including the effect of a shrinking radius of the sphere of captured dark matter [93]. Self-capture of dark matter in neutron stars has been considered in the case in which thermalization is rapid [97]. New here is the consideration of the region of parameter space in which thermalization of the dark matter within the neutron star is fairly late on the scale of the age of the neutron star. We find that in order for bosonic dark matter self-capture to be important for neutron star disruption, dark matter densities need to be on the order of $\rho_\chi = 10^3$ GeV/cm^3. Only for dark matter masses less than approximately 10 GeV could dark matter potentially disrupt neutron stars even with such large ambient dark matter densities.

IV. PUBLICATIONS AND PRESENTATIONS

Papers Published in Final Renewal Period, March 1, 2010 - April 30, 2013

- A. Denbleyker, Daping Du, Yuzhi Liu, Y. Meurice, and Haiyuan Zou, *Fisher's zeros as boundary of renormalization group flows in complex coupling spaces*, Phys. Review Letters **104**, 251601, 2010.
- A. Bazavov, A. Denbleyker, Daping Du, Yuzhi Liu, Y. Meurice, and Haiyuan Zou, *Fisher's zeros as boundary of RG flows in complex coupling space* arXiv:1011.1675, submitted to the POS for Lattice 2010.
- A. Bazavov, A. Denbleyker, Daping Du, Yuzhi Liu, Y. Meurice, and Haiyuan Zou, *Fisher's zeros as boundary of RG flows in complex coupling space* arXiv:1011.1675, POS for Lattice 2010.
- Y. Liu and Y. Meurice, *Lines of Fisher's zeros as separatrices for complex renormalization group flows*, Phys. Rev. **D 83** 096008 (2011).
- Y. Meurice and H. Zou, *Complex RG flows for 2D nonlinear O(N) sigma models*, Phys. Rev. **D 83** 056009 (2011).
- Y. Meurice, R. Perry, and S.-W. Tsai, Editors of the theme issue: *New applications of the renormalization group method in physics*, Phil. Trans. R. Soc. **A 369** (2011).
- Y. Meurice, R. Perry, and S.-W. Tsai, *New applications of the renormalization group method in physics, a brief introduction*, Phil. Trans. R. Soc. **A 369** 2602 (2011).
- Y. Meurice, *Dynamical Gauge Fields on Optical Lattices: A Lattice Gauge Theorist Point of View*, Summary of a poster presented at KITP in October 2011, [arXiv:1101.5369 [quant-ph]].
- Y. Meurice, Remarks about Dyson's instability in the large-N limit, e-Print: arXiv:1203.2256 [hep-th].
- Daping Du, C. DeTar, A. Kronfeld, J. Laiho, Y. Meurice and the Fermilab Lattice and MILC Collaborations, $B_s \to D_s/B \to D$ semileptonic form factor ratio and their application to $BR(B_s^0 \to \mu^+\mu^-)$, Phys. Rev. **D 85**, 114502 (2012).

- A. Bazavov, B. A. Berg, Daping Du, and Y. Meurice, Y. Liu and Y. Meurice, Density of states and Fisher's zeros in compact U(1) pure gauge theory, Phys. Rev. **D 85**, 056010 (2012).
- Fisher zeros and conformality in lattice models Yannick Meurice (Iowa U.), Alexei Bazavov (Brookhaven), Bernd A. Berg (Florida State U.), Daping Du (Iowa U. Fermilab Illinois U., Urbana), Alan Denbleyker (Iowa U.), Yuzhi Liu , Donald K. Sinclair , Judah Unmuth-Yockey, Haiyuan Zou . Oct 2012. 7 pp. Published in PoS LATTICE2012 (2012) 229
- Jon A. Bailey, A. Bazavov, C. Bernard, C. M. Bouchard, C. DeTar, Daping Du,*, A. X. El-Khadra, J. Foley, E. D. Freeland, E. Gmiz, Steven Gottlieb, U. M. Heller, Jongjeong Kim, A. S. Kronfeld, J. Laiho, L. Levkova, P. B. Mackenzie, Y. Meurice, E. T. Neil, M. B. Oktay, Si-Wei Qiu, J. N. Simone, R. Sugar, D. Toussaint, R. S. Van de Water, and Ran Zhou, Refining new-physics searches in $B \to D\tau\nu$ decay with lattice QCD, Published in Phys.Rev.Lett. 109 (2012) 071802
- Form factors for semi-leptonic B decays Ran Zhou, Steven Gottlieb (Indiana U.), Jon A. Bailey (Seoul U.), Daping Du, Aida X. El-Khadra, R.D. Jain (Illinois U., Urbana), Andreas S. Kronfeld, Ruth S. Van de Water (Fermilab), Yuzhi Liu, Yannick Meurice (Iowa U.). Nov 2012. 7 pp. Published in PoS LATTICE2012 (2012) 120
- Local gauge symmetry on optical lattices? Yuzhi Liu (Iowa U., Fermilab), Yannick Meurice (Iowa U.), Shan-Wen Tsai (UC, Riverside). Nov 2012. 6 pp. Published in PoS LATTICE2012 (2012) 246
- Y. Meurice, Accurate exponents from approximate tensor renormalizations, Phys.Rev. **B 87** 064422 (2013)
- Exact blocking formulas for spin and gauge models Yuzhi Liu , Y. Meurice (The University of Iowa), M.P. Qin (IOP Chinese Academy of Sciences), J. Unmuth-Yockey (The University of Iowa), T. Xiang, Z.Y. Xie, J.F. Yu (IOP Chinese Academy of Sciences), Haiyuan Zou (The University of Iowa). Jul 24, 2013. 12 pp. e-Print: arXiv:1307.6543, submitted
- T. Guver, A. E. Erkoca, M. H. Reno and I. Sarcevic, "On the capture of dark matter by neutron stars," arXiv:1201.2400.
- Y. S. Jeong (Yonsei University, Seoul, Korea), C. S. Kim (Yonsei University, Seoul, Korea) and M. H. Reno (University of Iowa), "Majorana dark matter cross sections with nucleons at high energies," Physical Review D 86 (2012) 094025, published 16 Nov 2012.
- Y. S. Jeong (University of Iowa), M. H. Reno (University of Iowa) and I. Sarcevic (University of Arizona, Tucson, AZ), "Radio Cherenkov signals from the Moon: neutrinos and cosmic rays," Astroparticle Physics 35 (2012) 383, published Jan 2012.
- A. E. Erkoca (University of Arizona), M. H. Reno (University of Iowa), I. Sarcevic (University of Arizona, Tucson, AZ), "Probing dark matter models with neutrinos from the Galactic center," Physical Review D (2010) 113006, published 6 Dec 2010.

- A. Bulmahn (University of Iowa), M. H. Reno (University of Iowa), “Secondary atmospheric tau neutrino production,” Physical Review D 82 (2010) 057302, published 21 Sep 2010.
- Y. S. Jeong (University of Iowa), M. H. Reno (University of Iowa), “Tau neutrino and antineutrino cross sections,” Physical Review D 82 (1010) 033010, published 19 Aug 2010.
- Y. S. Jeong (University of Iowa), M. H. Reno (University of Iowa), “Quark mass effects in high energy neutrino-nucleon scattering,” Physical Review D 81 (2010) 114012, published 7 Jun 2010.
- A. E. Erkoca (University of Arizona), G. Gelmini (UCLA, Los Angeles, CA), M. H. Reno (University of Iowa), I. Sarcevic (University of Arizona, Tucson, AZ), “Muon fluxes and showers from dark matter annihiliation at the Galactic center,” Physical Review D 81 (2010) 096007, published 25 May 2010.
- A. Bulmahn (University of Iowa) M. H. Reno (University of Iowa), “High energy leptons from muons in transit,” Physical Review D 82 (2010) 053003, published 4 Mar 2010.

Talks presented during final renewal period

- Y. Meurice, ”Complex zeros of the beta function, confinement and discrete scaling”, New applications of the renormalization group method in nuclear, particle and condensed matter physics (INT-10-45W) February 22 - 26, 2010.
- Y. Meurice, ”Renormalization Group in the Complex Domain”, Washington University, St Louis, March 17, 2010.
- Y. Meurice, ”Complex RG flows”, Aspen Center for Physics, June 9, 2010.
- Y. Meurice, ”Fisher’s zeros as boundary of RG flows in complex coupling space”, Lattice 2010, Villasimius, June 18 2010.
- Y. Meurice, ”Fisher’s zeros as boundary of RG flows in complex coupling space”, Univ. of Utrecht , August 10, 2010.
- Y. Meurice, ”Fisher’s zeros as boundary of RG flows in complex coupling space”, 5th ERG Conference, Corfu, September 14, 2010.
- Y. Meurice, ”Dynamical Gauge Fields on Optical Lattices : A Lattice Gauge Theorist Point of View”, KITP Conference: Frontiers of Ultracold Atoms and Molecules, Oct 11-15, 2010 .
- Y. Meurice, ”Fisher’s zeros as the Boundary of RG flows in complex coupling space”, UCLA, October 15, 2010.
- Y. Meurice, ”Fisher’s zeros as the Boundary of RG flows in complex coupling space”, UC Riverside, October 18, 2010.

- Y. Meurice, “Confinement and Walking Coupling Constants: A Renormalization Group Point of View”, Argonne Nat. Lab. (May 2011).
- Y. Meurice, “Confinement, RG flows in the complex coupling plane and Fisher’s zeros”, CAQCD (Minneapolis May 2011),
- Yannick Meurice, “QCD calculations with optical lattices?”, Lattice 2011, (July 2011).
- Y. Meurice, “Fisher’s zeros, complex RG flows and confinement in LGT models” , (APS-Prairie, Nov. 2011)
- Y. Meurice, Fishers Zeros, Complex RG Flows andConfinement in Lattice Models, Miami 2011, December 2011
- Y. Meurice, Renormalization Group Approach of Scalar Field Theory, U. Rochester, April 2012
- Y. Meurice, Lattice 2012, Cairns, Australia, June 2012
- Y. Meurice, KITPC Program “Critical Behavior of Lattice Models,” July-August 2012
- Y. Meurice, ERG 2012, Aussois, France, September 2012, Beyond the Local Potential Approximation for lattice models?
- Y. Meurice, APS March meeting 2013, Continuum limits of 12 flavor QCD
- Y. Meurice, BNL, Fisher’s zeros in spin/gauge models and beyond the standard model, April 2013
- Y. Meurice, Stony Brook, Dyson instability beyond the standard model, April 2013
- Y. Meurice, Baruch College, Alternatives to Monte Carlo, April 2013
- Y. Meurice, Syracuse Lattice models near conformality, April 2013
- M. H. Reno, Atmospheric lepton fluxes at high energies, IceCube Particle Astrophyscis Symposium, Madison, WI, 13-15 May 2013
- M. H. Reno, Neutron star constraints on asymmetric bosonic dark matter, April APS Meeting, Denver, CO, 13-16 April 2013 (contributed talk)
- M. H. Reno, The Moon as a Detector for Extreme-Energy Cosmic Rays, Cosmic Frontier, SLAC, Stanford, CA, 6-9 March, 2013.
- M. H. Reno, Muons and neutrinos from atmospheric charm, theoretical consideration, Miami 2012, Ft. Lauderdale, FL, 15-20 December, 2012
- M. H. Reno, Prompt leptons from atmospheric charm production, Eleventh Conference on the Intersections of Particle and Nuclear Physics, St. Petersburg, FL, May 29-June 3, 2012

- M. H. Reno, Radio Cherenkov Signals from the Moon: Neutrinos and Cosmic Rays, seminar at the University of Arizona, January 12, 2012.
- M. H. Reno, "Neutrinos from charm production: atmospheric and astrophysical applications," Eleventh Workshop on Non-Perturbative QCD, l'Institut d'Astrophysique de Paris, France, June 6-10, 2011
- M. H. Reno, Argonne National Lab High Energy Physics seminar, "Neutrinos from charm production: atmospheric and astrophysical applications," June 1, 2011.
- M. H. Reno, University of Arizona Colloquium and ADVANCE lecture, "Neutrinos, nature's messengers," December 3, 2010.
- M. H. Reno, University of Oklahoma Colloquium, "Cosmic rays and atmospheric leptons: probes of the standard model and beyond," November 4, 2010.
- M. H. Reno, "Neutrinos from dark matter," ICATPP Conference on Cosmic Rays for Particle and Astroparticle Physics, Villa Olmo, Como, Italy, October 7-8, 2010.
- M. H. Reno, "Neutrino signals of dark matter," Universite de Paris VII, October 5, 2010.
- M. H. Reno, "Neutrino signals of dark matter in the galactic center," Novel Searches for Dark Matter 2010 Workshop, Center for Cosmology and Astroparticle Physics, Ohio State University, July 5-6, 2010.
- M. H. Reno "Neutrino cross sections at 5-50 GeV," Low-Energy Neutrino Workshop, Penn State University, July 1-2, 2010.

V. GRADUATE STUDENTS DURING FINAL RENEWAL PERIOD

Students of Y. Meurice

- Zech Gelzer, PhD expected in 2017.
- Judah Unmuth-Yockey, PhD expected in 2016.
- Haiyuan Zou, PhD expected in 2014.
- Alan DenBleyker, PhD expected in 2013.
- Yuzhi Liu, PhD, July 2013, "Renormalization Group and Phase Transitions in Spin, Gauge and QCD-like Theories," position in September 2013 as a postdoc at the University of Colorado, Boulder. He was supported by a URA fellowship at Fermilab from August 2012 to August 2013.
- Daping Du, Phd, July 2011, "Fisher's zeros in lattice gauge theory." He was also at Fermilab with URA support in 2011. He had a postdoc at U. Illinois in Urbana Champaign and is starting another one at U. of Syracuse in August 2013.

Students of M. H. Reno

- Yu Seon Jeong, PhD, July 2011, "Quark and lepton mass effects and the observational constraints on the high energy neutrino cross section," current position, postdoctoral appointment, Yonsei University, Seoul, Korea.
- Alexander Bulmahn, PhD, May 2010, "Lepton pair production in high energy μA scattering: cross sections, energy loss and applications to underground lepton production," current position, lecturer, Department of Physics and Astronomy, University of Montana.

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