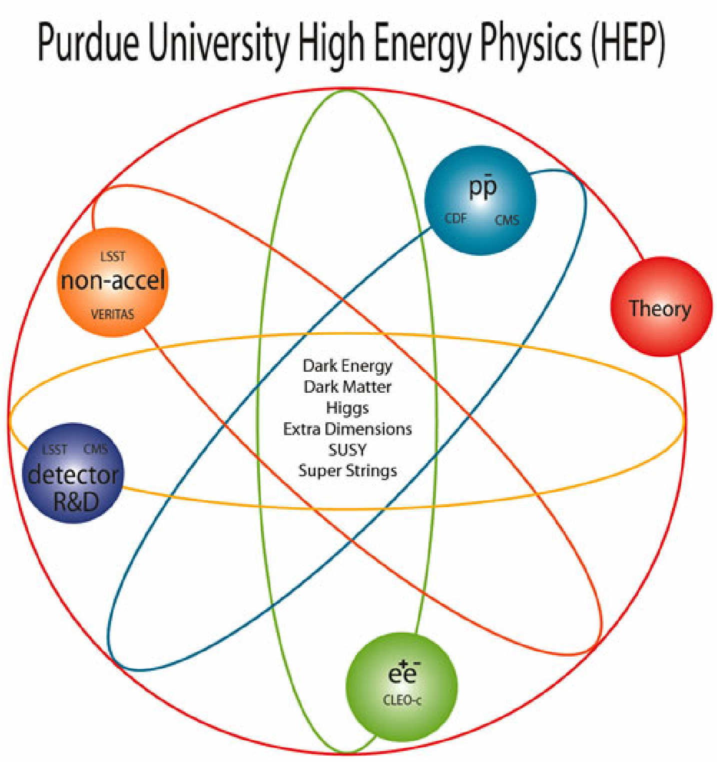

AN EXPERIMENTAL AND THEORETICAL HIGH ENERGY PHYSICS PROGRAM

Ian Shipsey, Principal Investigator
Professor of Physics
shipsey@purdue.edu

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Department of Physics
Purdue University
West Lafayette, IN 47907-2036

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PURDUE
UNIVERSITY

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THE PURDUE HIGH ENERGY PHYSICS PROGRAM
Overview

The Purdue High Energy Physics Group conducts research in experimental and theoretical elementary particle physics and experimental high energy astrophysics. Our goals, which we share with high energy physics colleagues around the world, are to understand at the most fundamental level the nature of matter, energy, space and time, and in order to explain the birth, evolution and fate of the Universe.

As of April 30 2012, the Purdue group members supported on the grant were: **Experiment—11 faculty** (7 Full: Barnes, Bortoletto, Cui, Finley, Garfinkel, Miller, Shipsey; 3 Associate: Jones, Neumeister, Peterson). **Research staff**: Arndt (Engineer), Bolla (Engineering Physicist), Laasanen, Merkel, Sembroski (Senior Scientist); 9 post doctoral fellows, 10 graduate students, and approximately 10 undergraduate students. **Theory—5 faculty** (4 Full: Clark, Fischbach, Khlebnikov, and Love; 1 Associate: Kruczenski), 2 post docs and typically 7 graduate students. The theory graduate students and most undergraduate students are not supported on DOE base funds.

Founded in the late 1950's, the Purdue High Energy Physics group played leading roles in the C0, HPW, Haleakala, HRS, CDF, CLEO, L3, and Whipple experiments. The experiments in which we are currently involved are: CDF, CLEO-c, CMS, LSST, and VERITAS. A brief description of our past work is in the remainder of this document.) We have been instrumental in establishing two major in-house facilities: The Purdue Particle Physics Microstructure Detector Facility (P3MD) in 1995 and the CMS Tier-2 center in 2005. The research efforts of the theory group span phenomenological and theoretical aspects of the Standard Model as well as many of its possible extensions. Recent work includes phenomenological consequences of supersymmetric models, string theory and applications of gauge/gravity duality, the cosmological implications of massive gravitons, and the physics of extra dimensions.

Major HEP Research Facilities at Purdue

The University has been very supportive over the last fifteen years both in terms of infrastructure and financial support. This support, in partnership with funds from the DOE and NSF, has been crucial to the establishment of two major particle physics research facilities at Purdue.

The Purdue Particle Physics Microstructure Detector Facility (P3MD)

The Purdue Particle Physics Microstructure Detector Facility (P3MD) is a suite of three modern, fully-equipped clean rooms with total space in excess of 3,500 sq. ft. P3MD was described by several DOE reviewers as "a nationally significant facility." Initial funding came from an NSF NYI Award to Shipsey and a NSF CAREER Award to Bortoletto. P3MD has made major contributions to the national program with the construction and testing of the CLEO III SVX, the design and testing of the sensors for the CDF Run IIa SVX, and the design and testing of the sensors and fabrication of the sensors-ROC-very high density interconnect subassemblies of the CMS forward pixel detector. The current projects are the LHC upgrade pixel detector and the LSST camera. P3MD has provided training in advanced instrumentation techniques for over 40 undergraduates. Further information is available in our past proposals and continuation reports.

The US CMS Tier-2 Computing Center at Purdue University

The CMS Tier-2 Center at Purdue (Neumeister, PI) plays a critical role in the Purdue contributions to USCMS and CMS. Over the past year, Purdue has been building and operating reliable software and hardware infrastructure to meet the needs of the USCMS effort, as well as undertaking strategic research and integration projects. It is the largest Tier-2 center in USCMS. Further information is available in our past proposals and continuation reports.

Education and mentoring:

We proudly list some of our contributions to education and mentoring.

Undergraduate: We pro-actively include undergraduates in our research. The undergraduates are drawn from the Department of Physics and the colleges of Engineering and Science. As Purdue's College of Engineering is ranked in the top ten in the country, the students are very capable of research at the University level. Seventeen undergraduates helped to build the CLEO III SVX, and a similar number have been involved in the construction and testing of the CMS Fpix detector and in the construction of VERITAS. The Theory group has mentored a number of undergraduate students who have co-authored papers in top-tier physics journals. Our better undergraduate majors progress to the finest graduate schools in the country most recently Berkeley, Chicago, Cornell, Penn, Princeton, MIT, Yale, Stanford, and UIUC. The undergraduates are supported on University funds or DOE/NSF/NASA project funds.

Graduate and postgraduate: Purdue enjoys a strong reputation internationally, enabling us to attract excellent graduate students, mostly from abroad. Between 1993 and 2011 there have been 31 experimental Ph.Ds awarded: 11 CDF, 11 CLEO, 1 CMS, 8 VERITAS/Whipple. Fifteen of our former students are now faculty members or scientists at National Labs. Nine work in industry, finance and education, and seven are post docs. Since 1993 the theory group has produced 10 PhDs; seven are now in the academic community, two in industry, and one in the military. The Theory group has also mentored 16 DOE supported postdoctoral research associates (not counting the current two) since 1988. Nine are currently either (US or overseas) university faculty or scientists at (US or overseas) National Labs, four work in industry, one is a postdoctoral research associate, one is a high school physics teacher and one is deceased.

Outreach to the Educational Community

Particle physics group members (Shipsey) were co-founders with Giordano (a condensed matter faculty member) of the Purdue NSF-funded Research Experience for Undergraduates (REU) program. Particle physics faculty routinely serve as REU mentors. Since 1999 approximately 120 students from primarily undergraduate research institutions have passed through this program and many have gone on to graduate school. Bortoletto founded a NSF Quarknet center at Purdue in 2003. Jones plays a strong role in center operation. Bortoletto initiated Hands on Particle Physics Master classes in 2009 for Indiana high school students. We have also organized scientific shows for area schools with audiences of 500 students, including Super Strings (Shipsey) and SuperScientific Circus (Miller). The astrophysics group regularly participates in outreach activities to the West Lafayette and Tippecanoe county community through open houses at the department's observatory in conjunction with the local amateur astronomy society. The events, held four times per year, regularly draw hundreds of individuals, and are a vehicle for the community to glimpse the research activities of the Purdue high energy astrophysics group. Members of the group also give public lectures, recent examples include "The LHC" by Shipsey at the Carnegie Institute in Washington D.C., and at Purdue.

Bortoletto has initiated several programs aimed at increasing the participation of women and minorities in Physics. She was the founder of the Purdue Women in Physics group and she serves as the advisor of the undergraduate women in physics organization. She started ScienceScape, a camp for middle school women. In 2011 she organized the Midwest undergraduate women in physics conference that attracted over 100 undergraduate students from all over the Midwest to Purdue. She is also organizing with Bonnie Fleming of Yale the group that oversees the planning of this conference series across the US. Under the leadership of Bortoletto and Fleming, the conference is growing from four sites (Northeast, Midwest, Southeast, California) to include also the Northwest and the Southwest.

Service to the Physics Community

Our faculty serve the community through peer review of proposals of other university groups supported by DOE, NSF and NASA, reviews of proposals submitted to the DOE OJI, SBIR and ADR, reviews of scholarly journal articles, panel reviews conducted by DOE, NSF, NASA and NSERC(Canada), SUSSP (U.K.) and through service on National committees.

Selected Recent Recognition and Service of Purdue Group Members by the Community:

Bortoletto**:**	Fermilab Program Advisory Committee (2011-2015); member, DOE/NSF High Energy Physics Advisory Panel (2005-8); DOE/NSF Particle Physics Project Prioritization Panel (P5) (2005-8); APS DPF Executive Committee, Fermilab URA, APS Fellow (2004).
Cui:	Member, Fermi Users Committee (2009-2012); chair, Fermi Guest Investigator Program Review Panel (2008, 2009, 2011); co-chair NASA's Small Explorer Program and Missions of Opportunity Program Review Panel (2011).
Finley**:**	VERITAS Collaboration Board Chair (2007-) chair, VERITAS Executive Committee (2007-2010); member, VERITAS Internal Proposal Committee (2010 -); chair, VERITAS Speakers Bureau (2011 -); chair, NASA Chandra peer review panel (compact objects and SNRs) (2011).
Fischbach**:**	APS Fellow (2001)
Jones**:**	FNAL Users Executive Committee (2007-2009); NSF CAREER Award (2010-2015)
Kruczenski:	Alfred P. Sloan Research Fellow (2009-2011) and NSF CAREER Award (2010-2015)
Love**:**	APS Fellow (1999)
Neumeister:	DOE OJI Award (2006).
Shipsey**:**	Chair line Division of Particles and Fields, APS (2012-2015), Member, International Committee for Future Accelerators (ICFA), Chair, DOE Electron Ion Collider Instrumentation Panel (2011); Chair, APS DPF Taskforce on Instrumentation (2011); member SLAC Board of Overseers Policy Committee (2011-2013), member, U. Chicago Board of Governor's of ANL Physical Sciences Directorate Review Committee, member, DOE/NSF HEPAP (2010-2013); member, Particle Astrophysics Scientific Assessment Group, a HEPAP subpanel; member, LSST Board of Directors (2010-2013); Chair, APS Panofsky Prize Committee (2004-6); member, FNAL PAC (2007-11); Chair, Canadian Participation in B physics (NSERC, 2007); DOE Committee of Visitors (2007); APS Fellow (2002); EPS Particle Physics Prize awarded to NA31 (2005).

We also organize and host conferences, for example, *Standard Model Benchmarks at the LHC and Tevatron* (one of four LHC workshops organized by Shipsey in 2010-11); *Beyond 10E34: Physics at a Second Generation B Factory* (Shipsey, 2000); and *Vertex 2000* (Bortoletto 2000).

Support for P3MD, the Tier-2 center and the reduced and waived IDC rates combined with the supportive faculty hiring environment illustrate the strong commitment of the Department of Physics, the College of Science and the University to the current program in high energy physics and to the future of the program. Purdue recognizes not only the intellectual significance of the research but also how it contributes to the education of both graduate and undergraduate students. We expect this partnership between the university and DOE to continue, and to continue to be fruitful.

Purdue research in high energy physics is a strong and vital enterprise making critical contributions to the field. We love our work. There is nothing we would prefer to be doing. We are grateful for the strong support our research receives from the University, the College of

Science, and the Department. We are profoundly grateful for the support we have received from the U.S. taxpayer through the Department of Energy during the period of this grant: 1991-2012. It is a privilege, and we have strived to be worthy of it.

Hadron Collider Physics at Purdue 1991 – 2012

This is a short summary of the ppbar and pp physics program at Purdue between 1991 and 2012. Extensive details can be found in our previously submitted progress reports and grant renewal documents submitted to the DoE

CDF (Virgil Barnes, Daniela Bortoletto, Art Garfinkel, Matthew Jones)

Purdue has maintained a strong presence in the CDF collaboration with Garfinkel and Barnes contributing to the design and construction of the central and end-wall calorimeters from 1981 onwards. Starting in 1994, our CDF group made significant contributions to the detector upgrade: Bortoletto and Garfinkel designed sensors for the SVXII silicon detector and participated in its construction, commissioning and operation, Barnes provided the radioactive source calibration system for the upgraded plug calorimeter, while Jones was responsible for the operation of the Time-of-Flight detector and the integration of new Level 1 and Level 2 trigger electronics. The development of sensors for the SVX2, led by Bortoletto, was particularly important for Purdue and the DoE since it facilitated our lead roles in the CMS at LHC forward pixel detector and its future upgrades.

The Purdue group has participated in many high-profile analyses of data recorded with the CDF detector, including the discovery of the top quark, exotic particle searches, and studies of hadrons containing heavy quarks. The Purdue group was a major player in the top discovery and the measurement of the top production cross section at the Tevatron. The thesis of our student Mark Kruse, now a professor at Duke, studied for the first time top production using dilepton events. More recently Jones led the analysis effort that resulted in the first direct observation of kaons produced in association with Bs mesons. This technique played a critical role in enabling oscillations to be observed in 2006. Recently, Jones' efforts at CDF provided the first complete analysis of the production cross section and polarization of Upsilon mesons, which is expected to at least partially resolve several outstanding questions that have plagued this field of research for several decades. Bortoletto has led several analyses that use data samples with missing energy and b-jets. This effort which led to 4 theses has provided a 3 sigma evidence for the low-mass Higgs produced in association with a Z or a W boson and decaying into b-jets. Her group used the same data sample to provide an important contribution to the first measurement of electroweak single top production at CDF and at the Tevatron. Bortoletto validated the multivariate analysis tools used in the Higgs search with a measurement of the tt production cross section and she deployed them in the measurement of diboson production and the search for a new T' particle decaying to top quark and a dark matter invisible particle.

CDF Publications

CDF has published over 575 papers since 1991. Our paper on the observation of the top quark has received almost 2,000 citations. Eight of our papers have received over 300 citations. The CDF experiment has provided important measurements of the production, decay, and properties of heavy particles such as top and bottom, electro-weak vector bosons (W and Z) and high-energy jets and photons.

CMS (Virgil Barnes, Daniela Bortoletto, Laszlo Gutay, Norbert Neumeister, Matthew Jones, and Ian Shipsey)

The Purdue group is one of the founding members of CMS, and our faculty have positions of responsibility and leadership within the collaboration. Bortoletto is a member of the CMS Phase 1 Pixel Upgrade management board; member of the CMS tracker phase 2 steering committee; and USCMS Upgrade coordinator. Neumeister is leader of the CMS Tier-2 Center at Purdue. Shipsey is Chairperson-elect of the CMS Collaboration Board, LHC Physics Center (LPC) co-Coordinator; he was recently CMS Quarkonia Taskforce co-Convenor. We contributed significantly to detector construction, software, computing and data analysis preparation and we are vigorously engaged in measurement and discovery with the excellent data that the LHC is delivering.

Instrumentation.

We have played a leading role in the design and fabrication of the forward pixel detector (1999-2007). Bortoletto lead the sensor design, and Shipsey lead the group that assembled all of the forward pixel detector modules at Purdue in P3MD. We were major players in the construction of the hadron-calorimeters (Barnes) and the Endcap Muon Chambers (Gutay). In close collaboration with FNAL and other universities, we will play a leading role in building the replacement pixel detector needed by 2016, and we will develop new sensors and novel mechanical support structures for a pixel detector for the SLHC CMS detector. Bortoletto is the overall USCMS SLHC detector coordinator.

Physics. CMS has extraordinary early discovery potential, and we were well-positioned to seize the opportunities that the LHC enables. The Purdue involvement in software and computing activities provides a strategic advantage for all physics analysis to be carried out at the LHC. CMS has selected Purdue to establish and operate a Tier-2 analysis center, and we believe the synergy between the Tier-2 activity and our physics analysis effort gives us a strong position within the CMS collaboration for physics analysis activities allowing us to maintain a strong research presence and leadership role.

The Purdue group made major contributions to the CMS Physics Technical Design Report (PTDR), CMS Cosmic Challenge (MTTC) and Computing, Software and Analysis (CSA) Challenge. Our group made major contributions to the development of reconstruction software used for both online event selection (HLT) and offline analysis. We were responsible for global/Level-3 muon reconstruction and have developed dedicated cosmic muon reconstruction software and tested its performance with data. Neumeister was convener of the muon Physics Object Group (POG) and the Muon Physics, Reconstruction and Selection (PRS) group.

The Purdue LHC physics program focused on muon detection. The CMS detector was designed with a flexible, robust and redundant muon system. Therefore muons are an ideal signature for the first phase of research at LHC. We have contributed to the discovery of the Higgs boson and the search for physics beyond the Standard Model, but we are also sharpening the tools needed for such discoveries. Shipsey led the first measurement of the Upsilon differential cross section at LHC now published in PRD and the analysis that provided the first hint of sequential Upsilon suppression in Heavy Ion data, which was predicted to be a smoking gun signal for the Quark Gluon Pasma. Neumeister has worked on the measurement of the Drell-Yan di-muon cross-section and the search for extra-dimensions of spacetime with muons.

Bortoletto has focused on the search for the Higgs boson in H-> ZZ in 2l2nu, 2l2q and 4l. Shipsey has looked for new physics via displaced dimuon vertices at large distances from the interaction point.

Publications

CMS has published over 188 papers since 1995. The paper on the CMS technical design report, volume II: Physics performance has received over 700 citations. The observation of a boson with a mass around 125 GeV is the first of what we expect to be many discoveries to emerge from the CMS physics program.

e^+e^- Physics at Purdue 1991 – 2012

This is a short summary of the e^+e^- physics program at Purdue between 1991 and 2012. Extensive details can be found in our previously submitted progress reports and grant renewal documents submitted to the DoE

CLEO (David H Miller, Bob McIwain (retired), Ed I Shibata (retired), Ian P J Shipsey)

Overview

The Purdue Group became members of the CLEO collaboration in 1986 after the successful completion of the HRS experiment at SLAC. During the period 1991 – 2012 we had a major leadership role in the evolution of the CLEO experiment (CLEO I.V, II, II.V, III and CLEO-c) as it became the preeminent experiment for the study of charm and bottom quarks. Data taking terminated at CESR in March 2008.

David Miller was the CLEO spokesperson from 1992-5 and had a leading role in the approval of CLEO III a major upgrade including a DoE funded, highly successful, silicon detector. The four layer silicon strip detector effort, led by Ian Shipsey, was particularly important for Purdue and the DoE since in partnership with the University the P3MD facility was created with engineering support for silicon detector design and fabrication. The silicon detector was the most sophisticated and complex built by universities without national lab involvement at that time and led to Purdue's world class silicon facility and our lead roles in the CMS at LHC forward pixel detector and the proposed LSST camera.

Ian Shipsey was co-Spokesperson of CLEO and then CLEO-c from 2001-4 and was a leader in the approval of CLEO-c. The goals of CLEO-c, which were met, were to enable the world-wide heavy quark flavor physics program to reach its full discovery potential by validating lattice QCD calculations with precision measurements of charm meson decay constants, charm semileptonic form factors and masses and widths in the charmonium system. Of equal importance, CLEO-c significantly advanced our understanding and control over strongly-coupled, non-perturbative quantum field theories, which could be crucial to interpret any strongly-coupled new physics discovered at the LHC.

Publications

The 446 CLEO publications since 1991 including Physical Review Letters: 194, Physical Review D and Rapid: 224 Physics Letters: 26, and Nuc. Inst. & Meth: 2**,** constitutes an outstanding record of achievement in forefront precision heavy quark flavor physics.

Shipsey and his post docs and students together with the Cornell and the SMU groups were leaders in the CLEO-c flagship charm semileptonic decay analyses. Results include the first observation of five new charm semileptonic decays modes and the most precise and robust measurements of the semileptonic form factors in $D \rightarrow K/\pi e\nu$ providing a crisp test of LQCD, and the most precise measurement of V_{cs} and most robust measurement of V_{cd}. These latter test the standard model explanation of quark mixing directly. By making the most precise measurements of charm leptonic decay constants and semi-leptonic form factors, CLEO-c made crucial tests of Lattice QCD. Validation of the charm LQCD calculations enables related calculations of B meson decay constants and form factors to be applied with increased confidence to measurements of B mixing to improve the determination of V_{td} and V_{td} / V_{ts}, and to $B \rightarrow \pi e \nu$ to extract V_{ub}, and thereby increase the sensitivity of B physics to physics beyond the standard model. This is shown in Figure 1. CLEO-c began this program and BES III will continue it.

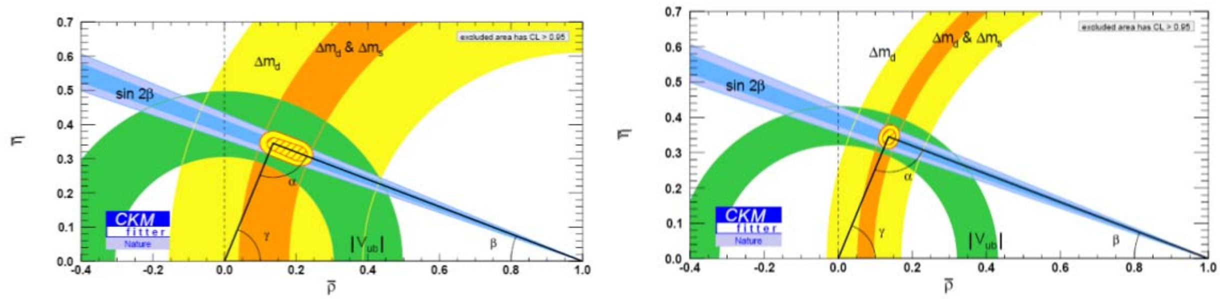

Figure 1. Constraints on the ρ-η plane from B mixing (orange and yellow bands) , |Vub| (green band) and sin2β (blue band). Left plot: status April 2008. Right plot: assuming theoretical uncertainties in charm decay constants and semileptonic form factors are reduced to 2% and 4% respectively with CLEO-c and BES III. The allowed values of ρ and η are shown by the circular yellow, and dashed red, regions that correspond to the 1 sigma and the 90% CL limit, respectively, as calculated with the CKM fitter program using only the inputs shown in the figure. Adding constraints from α, γ and CP violation in the K system would reduce the area of the allowed region only slightly. (Decotes-Genon & **Shipsey**)

Other measurements involving **Miller and Shipsey** include D hadronic branching fractions, 13 new decay modes of the ψ(2S) and 26 best upper limits on non-$D\overline{D}$ decays of the ψ(3770), the D_s decay constant D_s exclusive semileptonic branching ratios, Dalitz analysis of three body D decays, and searches for rare D decays. In addition Miller and Shipsey have had extensive involvement in a wide range of physics as chair or member of the internal review committees. Since 1991 the CLEO experiment has published 430 papers and Purdue faculty, postdocs and students have presented these results and overall reviews at most major conferences. More than a dozen Purdue students have received a CLEO PhD since 1990. The final one completed his thesis during 2012.

L3 at LEP (faculty Lazlo Gutay)

L3 was a major experiment at the Large Electron Positron Collider that began operation in August 1989 and finished in 2000 after reaching a final c.m. energy of 209 GeV. The measurements by the four LEP experiments tested theoretical predictions of the standard model to very high precision and established it's validity. Another notable achievement was determining that there are just three types of of light neutrino. The final energy reached was above the Z and W pair production thresholds and allowed the measurement of the triple gauge boson couplings. Accurate measurements of the electroweak parameters and the Z and W masses set limits on the Higgs boson mass: M_H> 114 GeV. Other physics topics were, two photon production of the D^*, Z pair production and the WW cross section and W decay branching ratios. The Purdue group had major responsibilities for the muon chamber system including DQM, characterizing chamber performance, tracking, timing and monitoring chamber performance.

<u>Non-accelerator Physics: 1991 – 2012</u>

The non-accelerator Physics program at Purdue over the period from 1991 – 2012 involved 3 faculty: James Gaidos (retired 2001), John P. Finley (1993 -), and Wei K. Cui (2000 -). The group participated in 2 main projects; the Whipple 10m imaging atmospheric Cherenkov telescope that established the field of very high energy (VHE) gamma-ray astronomy and VERITAS that evolved from it that now sets the standard in the field of VHE gamma-ray astronomy. Below we give a very brief summary of the activities and accomplishments over the period 1991 – 2012. Detailed descriptions of the group's activities and accomplishments over the years can be found in the yearly progress reports submitted as part of the reporting process.

<u>Whipple:</u> The Purdue group joined the Whipple collaboration in 1989 (**Gaidos**) after ramping down the program at Haleakala. **Finley** joined the collaboration upon his hiring in 1993 and **Cui** subsequently joined in 2000. The group had primary responsibility for data acquisition hardware/software, front end electronics and the high voltage systems over the period from 1991 – 2000. A major upgrade of the telescope was funded in 2000 and **Finley** was the coordinator for the upgrade and was responsible for the design, construction, assembly and testing of the high resolution camera while **Gaidos** assumed responsibility for the high voltage systems and the current monitoring systems. **Gaidos** retired in 2001 although he remained active in subsequent years.

Amongst the scientific achievements unique to the Whipple collaboration during the grant period were: detection of the first extra-galactic source of photons with energy above 100 GeV, Markarian 421(Punch et al., *Nature*, 358, 477, 1992.); first detection of extremely rapid flares from an extra-galactic object that called into question the standard model of acceleration in super massive black holes (Gaidos et al., *Nature*, 383, 319, 1996.); limits on the infrared background that constrained radiative neutrino decays and the contribution of massive particles to the dark matter problem (Biller et al., *PhRvL*, 80, 2992, 1998.); unique constraints on quantum gravity models based on Lorentz invariance violation (Biller et al., *PhRvL*, 83, 2108, 1999.)

The Whipple 10m telescope continued operations through 2009 when it was mothballed due to budgetary constraints. During the period from ~2005 until its mothballing it served as a monitoring instrument complementary to the VERITAS array. Purdue faculty, postdocs, and students continued their maintenance and upkeep of the instrument during that time as well as participating in the observational program when necessary.

<u>VERITAS:</u> VERITAS (the **V**ery **E**nergetic **R**adiation **I**maging **T**elescope **A**rray **S**ystem) is an array of 4 12m imaging atmospheric Cherenkov telescopes that grew out of the original Whipple collaboration. First proposed in 1996 the array was designed to provide a greater than 10 times increase in sensitivity over that achievable with a single telescope by providing stereo images of the air showers. The project was thoroughly vetted in the scientific community and received the endorsement of **PASAG**, **P5**, and the **2000 Decadal Review** where it was considered the top small budget project.

The Purdue group are key members of the original VERITAS collaboration and have responsibility for mirror facets and mountings for the light collectors (**Gaidos/Finley**), the data harvester and real-time analysis software (**Cui**), and the calibration and characterization of the focal plane detectors (**Finley**). In addition Purdue personnel are key contributors to the offline analysis software systems and the simulations of the detectors and air showers. Construction of the array commenced in 2004 and was completed (with 4 12m telescopes) in the fall of 2007. The project was completed on time and below budget!

The VERITAS array is currently the most sensitive imaging atmospheric Cherenkov telescope system in the world. Amongst its scientific accomplishments, to name a few, are: the detection of a new class of extra-galactic object that contributed to our understanding of the origin of the cosmic rays (Acciari et al., *Nature*, 462, 770, 2009.); a paradigm changing observation of pulsations from the Crab pulsar above an energy of 400 GeV (Aliu, et al., *Science*, 334, 69, 2011); deep observations of dark matter targets that constrain the large suite of models in the literature (Aliu, et a., *PhRvD*, 85, 2001, 2012). The array ultimately achieved a sensitivity almost 4 times the design sensitivity and the group is making key contributions to an upgrade scheduled for completion in 2012 that will increase the sensitivity by at least another factor of 2.

Publications: During the period from 1991 – 2012 there were over 135 referred publications produced with Purdue personnel as lead or co-authors. Notable amongst this large body of research are 4 *Nature* articles, 2 *Science* publications, 27 *Astrophysical Journal Letters*, and 3 *Physical Review* publications 2 of which that were *Letters*. This is an impressive ratio of more than 25% of the publications in high impact journals.

Postdocs, and Students: The personnel over the years that have participated in this program are still mostly active in the field today. Postdoctoral associates over the period were: Rodney Lessard (1998 – 2002) currently in the petrochemical industry in Canada; Abraham Falcone (2003 – 2007) currently on the scientific staff at Penn State Univ. Dept. of Astrophysics; Alexander Konopelko (2008 – 2009) currently on the faculty at Pittsburg State Univ. in Pittsburg, Kansas; and Mark Theiling (2010 – Present) who has completed 2 years of a 3 year appointment.

PhD students have also remained largely active in the area. The students that matriculated with the group were: Sangwook Park (PhD 1998 currently faculty at Univ. of Texas at Arlington); Radhika Srinivasan (PhD 1998 currently industry); Tony A. Hall (PhD 2000 currently chair of the department at Univ. of Arkansas – Little Rock); John P. Millis (PhD 2008 currently on the faculty at Anderson Univ.); Daniel Gall (PhD 2009 currently a postdoctoral associate at Univ. of Iowa); Benjamin Zitzer (PhD 2010 currently a postdoctoral associate at Argonne National Laboratory). There are currently 3 graduate students working with the group.

LSST at Purdue 2007-2012

One of the most exciting recent discoveries in physics is the evidence for the existence of dark energy. Observations of Type Ia Supernovae provided the first evidence for the acceleration of the expansion of the Universe and thus for the presence of dark energy (Perlmutter et al. 1999; Riese et al. 1998). The nature of dark energy is not understood. The simplest explanation is that dark energy represents a significant vacuum energy density expressed as Einstein's cosmological constant, Λ. Future measurements, however, may distinguish between the cosmological constant model and more elaborate models, such as a variable scalar field (quintessence), phantom energy models (kinetic quintessence), or a breakdown of the theory of general relativity on cosmological scales. The current cosmological model that includes both dark energy and the well-known mysterious dark matter is often referred to as the ΛCDM paradigm. The obvious difficulty with this model is that the vast majority of the composition of the present day Universe has to be studied through indirect means. Thus, a vast sector of the universe remains dark. Right now, the observational methods for “seeing" that dark sector are being pioneered.

LSST is a proposed joint DOE/NSF project to construct a survey telescope with unprecedented etendue. The amount of light that a telescope collects is proportional to its etendue, the product of its collecting area and field of view. LSST has an etendue of 300 m^2deg^2, which exceeds other telescopes by over an order of magnitude (and proposed telescopes by a factor of 6). This etendue is essential to produce a survey of the entire sky at sufficient depth to enable a wide variety of independent dark matter and dark energy measurements based on observations of the growth of structure and the expansion of the Universe. LSST is the top-ranked ground-based project in the Astro2010 Decadal Survey (which prioritized all astrophysics projects over this decade). LSST received DOE CD-1 earlier this year and the NSB of the NSF gave their approval this summer. will have its first light in 2020 after a roughly 6-year construction period if construction funding is included in the 2014 federal budget.

Purdue joined LSST in April 2007 with a strong scientific focus on dark energy. Dark energy presents such a fundamental problem about the laws of physics and the nature of our universe that the eventual solution will have to be derived, independently, from a variety of different techniques. The beauty of LSST lies in the fact that it combines several of the most powerful techniques in one experiment. One way of revealing the nature of dark energy is to study its effects on the distribution and growth of structures in the universe. Although this has been attempted with existing surveys, LSST aims at greatly improving the precision of the measurements, to a level that the data can be used to severely constrain cosmological models.
The approach that the Purdue group has primarily been concentrating on is to map the distribution of (mainly dark) matter through the effects of gravitational lensing. In the weak lensing regime, the effects manifest themselves in the correlated (induced) ellipticities of background galaxies. Quantifying such ellipticities leads to a determination of the shear field of foreground matter. To this end, the group has been developing and implementing algorithms for weak lensing analysis and testing them with high-fidelity simulated LSST data that are produced mainly at Purdue. Besides scientific interests, the group also has important roles in hardware and software development.

The Purdue LSST group is led by PIs Cui, Peterson and Shipsey. . Peterson's group is a part of the LSST image simulation (ImSim) group. It is the lead developer of the photon Monte Carlo simulator. The group has been performing image simulations to design dark energy measurements and for the data challenges organized by the LSST Data Management group. Cui's group, in collaboration with Peterson, has developed a simulator for the LSST Auxiliary Telescope, which will be used to provide critical calibrations of the main telescope. In parallel, it has also developed and implemented a number of algorithms that are needed for lensing studies. The group has participated in a number of blind tests to test the algorithms with satisfying results. Shipsey's group, in collaboration with Cui, is engaged in the design, development and verification of the corner rafts of LSST that house the wavefront curvature sensing and guiding functions of the LSST telescope. Purdue will be the fabrication site for these systems. We have provided CAD models of all components and assembly sequences and carried out thermal and structural studies of the cooling and support design. The group also plays a leading role in the development of wavefront reconstruction software, and is developing algorithms needed for lensing studies in collaboration with Cui and Peterson. Shipsey was elected to the LSST Board of Directors in 2009 for a four year term. He is Chair of the LSST Nominations Committee. In July 2011 he organized a non-advocate independent three-day Board of Directors review of LSST prior to the NSF PDR, and a subsequent follow-up mini-review. Reviewers were drawn from the particle physics, astrophysics and computer science communities. These reviews identified shortcomings, which the project subsequently addressed, and are widely credited with being a major factor in the successful outcome of the PDR.

Theory and Phenomenology (former Task B)

Faculty: Richard H. Capps (deceased), Thomas E. Clark, Sergei Khlebnikov, Luis Martin Kruczenski, Tzee-Ke Kuo (retired), Sherwin T. Love

Research topics included phenomenology of extensions of the standard model, neutrino physics, inflationary cosmology, string theory and applications of gauge/gravity duality.

DOE supported research of **T.E. Clark** and **S.T. Love** involved the introduction and analysis of various possible extensions of the standard model. Particular attention was focused on model independent consequences of supersymmetric extensions as well as on the dynamical structure of a variety of models involving strongly coupled dynamics. A systematic procedure was constructed which detailed the couplings of the Goldstinos (gravitinos) to matter and gauge fields Superspace representations as well as nonlinear realizations of supersymmetry in conjunction with other symmetries including *R* symmetry, global chiral symmetry, dilatations and superconfromal symmetries were constructed and analyzed. The currents associated with some of these symmetries were seen to form a supermultiplet structure. Other applications of supersymmetry included supersymmetric top condensate models and a strongly interacting extension of the minimal supersymmetric standard model. A minimal candidate for dark matter is provided by a stable standard model singlet hermitian scalar field. The effects of this singlet were explored in a Higgs as inflaton model. Imposition of the slow roll inflation cosmological constraints yielded restrictions on the allowed values of the Higgs boson mass, its coupling to the dark matter and the dark matter selfcoupling. An exact Wilson renormalization group equation was constructed which governs the scale dependence of the action for theories containing scalars and fermions and was used to analyze nonperturbative triviality and vacuum stability mass bounds. In models of more than four spacetime dimensions, effective actions for brane oscillations were obtained. One consequence manifests itself as the emergence of massive vector gauge fields. Their coupling to the standard model was deduced. The brane vectors are stable and weakly interacting, and therefore escape particle detectors unnoticed and are potential dark matter candidates. Accelerator and dark matter data was used to delineate experimentally excluded regions of brane vector parameter space. Approximate scale invariance plays a significant role in many diverse areas of theoretical physics. Quenched, planar QED exhibits a dynamical structure which mimics more complicated gauge theories with slowly running couplings such as walking technicolor theories. In collaboration with W.A. Bardeen, S.T. Love constructed an effective Lagrangian describing the dynamics of the composite scalar which plays an essential role in the effective dynamics.

Research of **S. Khlebnikov** involved development of semiclassical methods for applications in particle physics and inflationary cosmology. He developed (in collaboration with I. Tkachev) the first fully nonlinear method for studying inflaton decay in cases when it proceeds by amplification of quantum fluctuations to large (classical) values. This led them to the view of post-inflationary universe as a state of wave turbulence and to the prediction of a background of relic gravitational waves produced by such a state. Later, Khlebnikov applied a similar method to a study of the final (coarsening) stage of Bose-Einstein condensation (BEC) and gave analytical arguments and numerical evidence for a turbulent cascade of the particle number. This cascade determines the timescale of BEC in large volumes, a quantity that may be relevant to future laboratory experiments and is also of interest in astrophysical applications (BEC as dark matter).

Reductions from odd to even dimensionalities (e.g., 5 → 4), such as envisioned in some brane-world models present one with a puzzle: a mismatch between the ultraviolet (higher-dimensional) and infrared (lower-dimensional) anomalies. This applies to both local (gauge) and global currents. Khlebnikov (in collaboration with M. Shaposhnikov) considered the latter case and showed that the mismatch is accounted for by spectral asymmetry of the massive fermionic modes. This led to a better understanding of a class of extra-dimensional (axion-free) solutions to the strong CP problem.

The AdS/CFT correspondence realizes in practice the idea of describing gauge theories in terms of strings and provides a new tool for studying gauge theories at strong coupling. **Khlebnikov**, **Kruczenski** and postdoc G. Michalogiorgakis have used it to study shock waves in strongly coupled plasmas. While weak shocks, i.e., those of small amplitude, are well described within the hydrodynamic approximation, strong shocks are discontinuous within hydrodynamics, and resolving their profiles requires a microscopic description. In the case of a strongly coupled $N = 4$ super-Yang-Mills plasma, such a description is given in terms of gravity in an asymptotically AdS_5 space. Using linearized gravity, they have computed the penetration lengths of the shock's front and tail as functions of its velocity. This calculation provides a testing ground for phenomenological theories that are not directly based on microscopics but are often used for description of the quark-gluon plasma.

The work of **M. Kruczenski** relates primarily to string theory and in particular to its connection with gauge theories. His most recent work considers the application of integrability techniques to understand Wilson loops in the context of gauge/string theory dualities. According to the AdS/CFT duality, Wilson loops can be computed by finding minimal area surfaces in hyperbolic (Anti de Sitter) space. Using known mathematical results for such surfaces, **Kruczenski** together with his current and previous students R. Ishizeki, S. Ziama and A. Irrgang were able to find an infinite class of examples of surfaces ending on closed smooth contours. Previously only a handful of examples were known.

Other work of **M. Kruczenski** also relates to the AdS/CFT correspondence including the study of light-like Wilson loops, black hole entropy, summing planar diagrams in light cone gauge, etc. Those results helped in one way or another to better understand the connection between gauge theory and string theory.

Ephraim Fischbach – PI

Physics Beyond the Standard Model --- Project Summary

The effort of the PI, under what was formerly Task F, dealt with the phenomenology of new physics beyond the Standard Model. This effort has led to the following significant achievements during the course of this project.

SUMMARY OF PHENOMENOLOGY AND EXPERIMENT RESEARCH ACHIEVEMENTS

1. Derived stronger constraints on Non-Newtonian gravity over short distance scales from the Casimir Effect.
2. Implemented a new experiment to using the "iso-electronic technique" to improve the limits on new string-inspired forces in the Casimir regime.
3. Presented data from a variety of experiments pointing to a solar influence on nuclear decays, perhaps via neutrinos.
4. Developed a formalism which demonstrated that the experimentally observed negative values of
5. M^2 ($\bar{\nu}_e$) can be explained both qualitatively and quantitatively by the same mechanism that accounts for the periodicities observed in beta decay data.
6. Presented an analysis suggesting that we may be seeing evidence for massive gravitons on a cosmological scale.

Scientific Research Overview

Although our group (formerly Task F) is formally a theory group, our efforts have traditionally combined theory and experiment. Of the 18 papers produced by our group over the past 3 years, 4 have presented results from new experiments that we have designed and carried out at Purdue. An additional 8 dealt with phenomenological analyses of other data sets, and 6 were purely theoretical papers. The close connections among experiment, phenomenology, and theory in our group have produced a number of very interesting results during the past three years:

1. In our search for new string-inspired short-range forces we have published what are now the most stringent constraints in the ~100 nm distance scale. These constraints are quoted as Decca, et al. in the 2010 Particle Data Group [K. Nakamura, et al. (Particle Data Group) 2010 J. Phys. G: Nucl. Part. Phys. **37,** 075021, pp. 1362 and 1364].
2. We presented data which for the first time established a correlation between nuclear decay rates and Earth-Sun distance. This paper was cited by Science Direct as the #1 "Hottest Article" in Astroparticle Physics for the period July-September 2009, and as the #2 "Hottest Article" for the entire year October 2009 – September 2010.
3. We presented data from an experiment we carried out at Purdue in which we found strong evidence of a correlation between a drop in nuclear decay rate and the simultaneous occurrence of a solar flare. This paper was cited by Science Direct as the

#10 "Hottest Article" in Astroparticle Physics for the entire year October 2009 – September 2010, and will be discussed in detail below.

Constraining new forces implied by string theories and extra-dimensional physics using the Casimir Effect

This effort, which has been a central theoretical and experimental focus of our group for several years, aims at finding evidence for new forces and string-inspired extra dimensional physics by detecting deviations from Newtonian gravity over short distances. Our motivation for these searches comes from two currently related themes: 1) unification theories that incorporate *n* compact extra spatial dimensions (of size R(*n*)) predict deviations from Newtonian gravity over sub-mm scales, when R(*n*) is itself a sub-mm length; and 2) String theories and other extensions to the Standard Model predict the existence of new light bosons, whose exchange leads to Yukawa corrections to gravity.
The focus of our group is a possible deviation from Newtonian gravity over distance scales of order ~100nm. For experiments whose test masses are separated by $\leq$ 1 *nm* the dominant background arises from the Casimir force.

Current experimental limits over sub- *m* scales allow for gravity-like interactions that are many orders of magnitude stronger than Newtonian gravity, and hence there is an obvious need for new experiments in this regime. In dealing with the Casimir force background, we have employed two approaches. In the *traditional approach*, we calculate the Casimir force between two small objects (typically a sphere and a flat plate), including all possible corrections. Then we can use any discrepancy between theory and experiment to set limits on possible new forces that could account for this discrepancy. We employed this approach to point out a possible discrepancy between our current data and our best theory of the Casimir force. At present there is a discrepancy between theory and experiment for separations below ~200nm, which increases at shorter separations. This behavior is consistent with what would be expected from a new short-range force--although our group is not claiming this at present. In the second approach, called the *iso-electronic technique*, we eliminate the contribution from the Casimir effect at the outset by comparing the forces between a given sphere and two different substrates having identical properties with respect to the Casimir force. This iso-electronic technique was first proposed by Krause and Fischbach by considering a Casimir force experiment comparing ^{58}Ni and ^{64}Ni, which have the same behavior with respect to the Casimir force but not other forces. Subsequently, we pointed out that the same effect could be achieved by comparing the Casimir forces between a test mass and two dissimilar materials covered with a common 150nm layer of gold. Our group pioneered the iso-electronic technique approach where we demonstrated that this approach provided an immediate improvement by a factor of ~10 over the previous approach.