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# Final Report: High Energy Physics Program (HEP) Physics Department, Princeton University

**DOE Grant#:** DEFG02-91 ER4067

for the period: October 1, 1991 to January 31, 2013

**Principal Investigators:** Daniel Marlow, Pierre Piroué, and A.J. Stewart Smith

### Abstract

The activities of the Princeton Elementary particles group funded through Department of Energy Grant# DEFG02-91 ER40671 during the period October 1, 1991 through January 31, 2013 are summarized. These activities include experiments performed at Brookhaven National Lab; the CERN Lab in Geneva, Switzerland; Fermilab; KEK in Tsukuba City, Japan; the Stanford Linear Accelerator Center; as well as extensive experimental and theoretical studies conducted on the campus of Princeton University. Funded senior personnel include: Curtis Callan, Stephen Gubser, Valerie Halyo, Daniel Marlow, Kirk McDonald, Peter Meyers, James Olsen, Pierre Piroué, Eric Prebys, A.J. Stewart Smith, Frank Shoemaker (deceased), Paul Steinhardt, David Stickland, Christopher Tully, and Liantao Wang.

# Contents

# 1 B Physics with BaBar

**Recent Personnel:** G. J. P. Elmer, D. Lopes Pegna, C. Lu, J. D. Olsen, W. R Sands, A. J. S. Smith

The BaBar experiment was formed in the fall of 1993 to build and operate the detector for the PEP-II Asymmetric *B*-Factory at SLAC. The primary goal of the BaBar research program is to study *CP* violation in the decays of the copious numbers of correlated pairs of $B$ and $\overline{B}$ mesons produced by tuning PEP-II to the $\Upsilon(4S)$ resonance. In its final phase of operation, PEP-II also accumulated unprecedented datasets at the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances, and the region just above the $\Upsilon(4S)$. The final $\Upsilon(4S)$ dataset includes $433\,\mathrm{fb}^{-1}$.

Princeton was the lead US institution in a US-Canada-Italy-France collaboration to build the central tracking drift chamber (DCH), and led the project to upgrade the original flawed muon system. Recent group members included Smith and Olsen; Research Staff Telnov and Lopes Pegna; Senior Scientist Elmer; Senior Technical Staff member Lu; Senior Engineer Sands; as well as several graduate and undergraduate students. Princeton faculty have provided leadership in many ways. Smith served as Spokesperson during the CP violation discovery (contributing to the 2008 Nobel Prize in Physics), Technical Coordinator, and System Manager for the DCH and Muon Upgrade systems; Olsen was Detector Control Coordinator, Muon Upgrade Commissioner, Charmless B Decays Working Group leader, and Physics Analysis Coordinator (2006-07). Elmer led the BaBar-Grid Computing Model. Sands was project engineer for the Muon Upgrade; Lu is a detector physicist who was instrumental in diagnosing the original muon system failure, and in the design and construction of the upgraded detector.

Our efforts in physics analysis have spanned the broad categories of *CP* violation studies and semileptonic $B$ decays, with an eye toward new physics. Olsen led the team that found the first evidence (and later observation) for direct *CP* violation in the B system (Phys. Rev. Lett. **93**, 131801 2004). Our final result using the full dataset, was recently published in Phys. Rev. D87, 052009 (2013). The technique for a related measurement, the time-dependent *CP* asymmetry in $B^0 \to \pi^+\pi^-$, which is sensitive to the CKM angle $\alpha$, was developed originally by Olsen in Phys. Rev. D **65**, 051101, 2002, and the final measurements were published in PRD87, 052009. Olsen (with student Biesiada) found the first evidence for the $b \to d$ decay $B^0 \to K^0\overline{K}^0$ (Phys. Rev. Lett. **95**, 221801, 2005), and performed the first measurement of *CP*-violating parameters in this mode, which surprisingly disfavors large positive values of the asymmetry (Phys. Rev. Lett. **97**, 171805, 2006). Other work performed by the group over the last decade include measurements of the CKM angle $\gamma$ (Phys. Rev. Lett. **95**, 121802, 2005, Phys. Rev. D **78**, 034023, 2008), $V_{\mathrm{cb}}$ (Phys. Rev. Lett. **104**, 011802, 2010), and early measurements of $\sin 2\beta$ using B-meson decays to D mesons. Lopes Pegna recently published one of the most talked about results in flavor physics in 2012: first evidence for the decays $B \to D^{(*)}\tau\nu$ (Phys. Rev. Lett. 109, 101802, 2012). As Olsen's group shifted to CMS the *BABAR* effort has steadily ramped down and is now effectively at an end, thus concluding nearly two decades of highly productive and influential work on CP violation by the Princeton HEP group led by Smith and Olsen. For a list of BaBar publications see : http://www-public.slac.stanford.edu/babar/Publications.aspx

## 2 The Belle Experiment at KEK

**Personnel:** Faculty: D. Marlow, E. Prebys; Research Associates: K. Hanagaki, A. Garmash, T. Lui, and T. Ziegler; Graduate Students: A.Tchouvikov, K. Korotushenko, C. Leonidopoulos, C. Mindas, and S. Vahsen.

Princeton's involvement in Belle started soon after the demise of the SCC in late 1993. Marlow and Prebys were founding members of Belle and made major contributions to three different hardware subsystems: the Silicon Vertex Detector (SVD), the Aerogel Cherenkov Counter (ACC) particle identification system, and the Resistive Plate Chamber (RPC) $K_L/\mu$ system. The group was also involved in early studies of $B$ mixing, the first measurements of CP violation in $B^0 \to J/\psi K_L$, as well as many other topics.

### 2.1 Silicon Vertex Detector

Approximately one year before KEK-B was slated to begin operation in 1998, it became apparent that the baseline design for Belle's SVD was in serious trouble. At the urging of Marlow and other senior members of the Belle collaboration, a review committee with members both internal and external to Belle was established. The committee confirmed that baseline design was unlikely to work and urged Belle to develop a back-up option. Physicists from KEK., Krakow, Osaka, Princeton, and Tokyo prepared a plan that relied on off-the-shelf detectors as much as possible, since there was no time to develop anything new. Princeton took the lead in developing a hybrid design in conjunction with the IDEAS company in Oslo, Norway. Princeton also took charge of fabricating DSP readout modules that were designed by Belle colleagues in Krakow.

The resulting design, worked well, but had limited radiation hardness. Since the cost of the detector was relatively modest, a complete spare was produced. This precaution turned out to be extremely well justified when the inner layer of the first detector was destroyed by synchrotron $x$-rays produced by the final focus elements in the initial pilot run of KEK-B. With suitable shielding in place, the replacement detector function well and allowed Belle to keep pace with its BaBar competition. In subsequent years, the Princeton group continued to collaborate with other Belle institutions on various follow-up designs of increasing radiation hardness.

### 2.2 ACC Particle Identification System

In the early day of Belle, the Princeton group advocated the use of the DIRC (Detection of Internally Reflected Cherenkov light) technology originally proposed by Ratcliff and collaborators at SLAC for particle identification. As part of the down-select process, Princeton successfully fabricated and tested the first DIRC detector to produce complete Cherenkov images[1]. We were able to do this in a short time by using an air standoff region, which eliminated numerous engineering challenges associated with a water-filled standoff, albeit at the cost of light yield and increased chromatic aberration. Despite this clear proof of principle, Belle ultimately selected a PID design based on Aerogel Cherenkov detectors[2] out of concerns that KEK did not have the engineering resources required to construct the full DIRC system.

Princeton continued in the PID subsystem, taking responsibility for the readout chain, which included the PMT bases, preamps, and readout boards. The ACC system worked reasonably well and ensured that Belle was able to produce a clean separation between the $B \to \pi^+\pi^-$ signal mode and the more copious $B \to K^+\pi^-$ background.

### 2.3 $K_L/\mu$ System

Working in close collaboration with colleagues from Virginia Tech and Japan, Princeton took a leading role in the construction of the Resistive Plate Chambers (RPC's) that were used to instrument the iron flux return of Belle[3, 4]. Princeton was responsible for the mechanical design of the of the barrel modules and the fabrication of the readout electrodes and the metal skins that covered the modules (Virginia Tech build the actual detector modules). In addition, Princeton designed and built the readout electronics, readout cables, and the gas system for both the barrel and end cap RPCs.

### 2.4 Physics Analysis

Graduate students Christos Leonidopoulos and Sven Vahsen were among the first cohort of students to complete Ph.D. dissertations based on data from Belle. Leonidopoulos did the first Belle analysis of $B$-mixing, which he used to set limits on possible CPT violating effects[**?**]. For his Ph.D. thesis, Vahsen played a key role in the $B^0 \to J/\psi K_L$ analysis of time-dependent CP violation[6][7], which provided an important cross check on the results from the so-called gold-plated mode $B^0 \to J/\psi K_S$. Other key contributions from the Belle group were made by postdoc Alexei Garmash[8][9].

## References


[1] C. Lu, D. R. Marlow, C. Mindas, E. Prebys, W. Sands and R. Wixted, "Detection of internally reflected Cherenkov light, results from the BELLE DIRC prototype," Nucl. Instrum. Meth. A **371**, 82 (1996).

[2] T. Iijima *et al.* [Belle Collaboration], "Aerogel Cherenkov counters for the Belle experiment," Nucl. Instrum. Meth. A **379**, 457 (1996).

[3] M. Yamaga *et al.* [BELLE Collaboration], "RPC systems for BELLE detector at KEKB," Nucl. Instrum. Meth. A **456**, 109 (2000).

[4] A. Abashian *et al.* [BELLE Collaboration], "The $K_L/\mu$ detector subsystem for the BELLE experiment at the KEK B factory," Nucl. Instrum. Meth. A **449**, 112 (2000).

[5] K. Abe *et al.* [Belle Collaboration], "Measurement of $B_d^0 - \bar{B}_d^0$ mixing rate from the time evolution of dilepton events at the $\upsilon_{4S}$," Phys. Rev. Lett. **86**, 3228 (2001) [hep-ex/0011090].

[6] K. Abe *et al.* [Belle Collaboration], "Observation of large CP violation in the neutral $B$ meson system," Phys. Rev. Lett. **87**, 091802 (2001) [hep-ex/0107061].

[7] K. Abe *et al.* [Belle Collaboration], "An Improved measurement of mixing induced CP violation in the neutral B meson system," Phys. Rev. D **66**, 071102 (2002) [hep-ex/0208025].

[8] A. Garmash *et al.* [BELLE Collaboration], "Dalitz analysis of the three-body charmless decays $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$," Phys. Rev. D **71**, 092003 (2005) [hep-ex/0412066].

[9] A. Garmash *et al.* [Belle Collaboration], "Study of $B$ meson decays to three body charmless hadronic final states," Phys. Rev. D **69**, 012001 (2004) [hep-ex/0307082].

# 3 DØ Experiment at the Tevatron

**Personnel:** C. Tully, A. Schwartzman, (Graduate Students) D. Gerbaudo, J. Haley, W. Fisher, H. Saka, R. Wagner

Over the past decade of Tevatron Run II operation several students and postdocs have made major contributions including initial commissioning, new physics searches, top-mass and cross-section measurements, diboson cross-section measurements, and the high-mass Higgs boson search. This list includes Jeremiah Mans who is now an associate professor at the University of Minnesota. Wade Fisher, headed the Tevatron Higgs combination effort, is an assistant professor at Michigan State University. Ariel Schwartzman working with Chris Tully made the first measurements of the top mass using Matrix Element methods modified to incorporate lifetime-time tagging and intrinsic light-quark jet energy scale calibration. Ariel Schwartzman is currently an assistant professor at SLAC. Joseph Haley is a tenure-track assistant professor at Oklahoma State University and headed the D0 Higgs search. Robert Wagner is a postdoc and lecturer at Illinois State University. Davide Gerbaudo is a research scientist at UC Irvine.

The precision measurement of the top quark mass continues to be one of the most important constraints in the precision electroweak program. This work complemented the previous precision measurement work completed at the L3 experiment at LEP. The Tevatron measurements gained enough precision to bring the top mass uncertainty down below the level where it would limit the prediction of the Higgs boson mass, which was accurately constrained to be below 154 GeV before its discovery at the LHC. The Matrix Element method used extensively for the top quark mass measurement continues to be a powerful technique for a wide range of searches and property measurements at the LHC. This work was a primary focus of Ariel Schwartzman and Chris Tully for many years. These same methods continued with higher statistics have pushed down the top quark mass measurement precision to better than 1 GeV.

Over the years 2008-2011, the Princeton research effort focused on the Higgs boson search. In an effort to emphasize the importance of the final Tevatron Higgs search results, Princeton hosted the 2011 DØ summer workshop with the theme "Analyzing the full Run II DØ data set." At the workshop a significant focus was put on providing final sensitivity and results on the Tevatron search on the timescale of summer 2012, and that was later achieved. Joseph Haley as a precursor to the Higgs boson search to heavy-flavor dijets measured the diboson cross section for the combination of WW and WZ production where one boson decays leptonically and the other hadronically. This work led to the first measurement of the cross section in this process to over 3 standard deviations and the direct reconstruction of the dijet mass of the W and Z boson in a topology common the HW/HZ searches. This work gained wide visibility and led to the appointment of Joseph Haley as the DØ Higgs group leader, taking over from Wade Fisher who went on to head the Tevatron Higgs combination work.

Davide Gerbaudo's was the leader of the high-mass $H \to WW$ search in the dimuon channel and provided this analysis as part of the 8.2 fb$^{-1}$ DØ/CDF Tevatron Higgs combination. Davide updated this analysis for the 2011 Lepton-Photon conference results, which in combination with the other D0 and CDF WW analyses achieved the first Higgs boson mass exclusion above the LEP limit. The exclusion limits from the Tevatron Higgs boson search that include contributions from Davide Gerbaudo's analysis are shown in Figure 1.

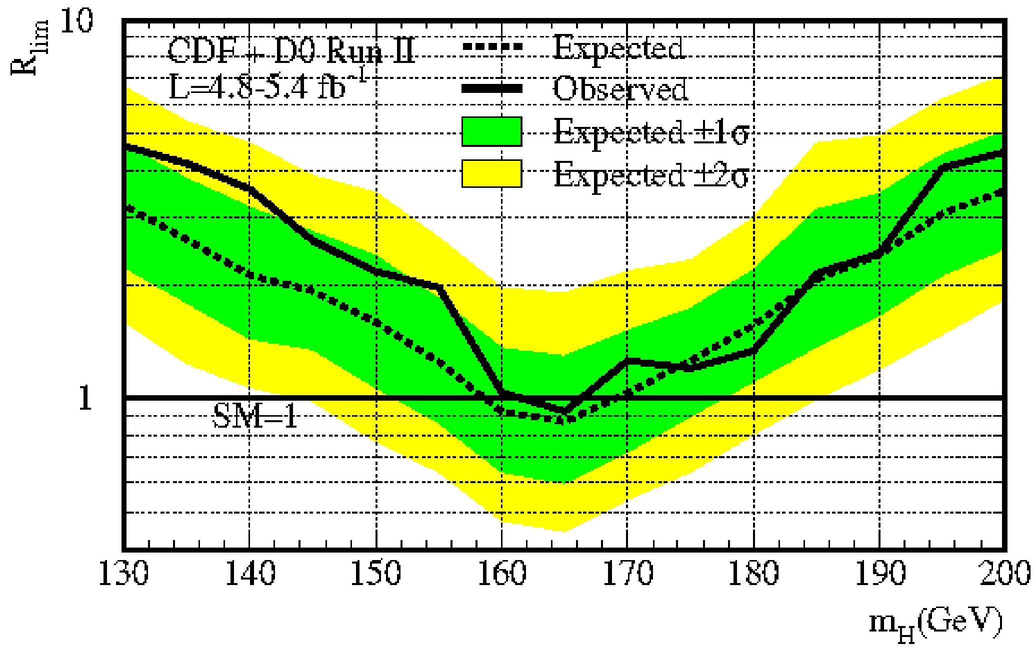


Figure 1: One of the landmark achievements of the Tevatron program was the ability to search in the intermediate mass range of the Higgs boson. The region in the vicinity of 165 GeV was excluded by the Tevatron analyses in advance of the discovery of the Higgs boson at the LHC at 125 GeV.

In 2011, Halil Saka investigated the third generation scalar leptoquark search in a new and unexplored final state. The $t\bar{t}\tau^+\tau^-$ final state is predicted by extended Higgs sectors such as that in $SU(5)$ grand unification theories. The kinematic accessibility is in the 180 to 250 GeV/$c^2$ mass region and has high signal-to-noise in the same-sign dilepton and trilepton channels. Halil completed a first analysis of this final state, and then with the concurrent operation of the LHC continued to work with this analysis on the CMS experiment at the LHC. Due to the large delivery of integrated luminosity by the LHC, the incremental benefit of pushing forward the $WW$ Higgs boson search and $3^{rd}$ generation lepto-quark searches at the Tevatron was marginal. The Princeton DØ group decided in late 2011 to redirect the Tevatron effort to CMS physics and detector R&D. Detector R&D has become a vital area of creative development, empowering new leaps in experimental particle physics for future experiments, and providing new opportunities for basic energy research in the US and internationally.

A complete list of DØ publications can be found at URL: http://www-d0.fnal.gov/d0_publications/.

# 4 The CMS Experiment at CERN

After a tremendously successful run campaign in 2011 and 2012, during which a new particle with properties consistent with the long-sought Higgs boson was discovered, the LHC will continue with a short $p$-Pb run in the early months of 2013, after which it will enter LS1, the first of two long shutdowns, extending through 2014.

A complete list of CMS publications, reports, etc., can be found at URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

## 4.1 Beam Radiation Monitoring

**Personnel:** D. Marlow and D. Stickland

Princeton has been active in the BRM for CMS since 2006. Our original motivation was to gain experience with the use of diamond detectors, but in view of the importance of the BRM to the health and well being of the CMS detector, we decided to make the BRM one of Princeton's key service contributions to CMS. David Stickland has held various leadership positions within the BRM group and has been proposed to lead the newly formed Beam Radiation Instrumentation and Luminosity (BRIL) subsystem.

The BRM's primary purpose is to monitor beam conditions near the CMS detector and to send a beam-abort signal to the LHC in the event that radiation losses rise to the level where the there is an immediate threat to the detector. It comprises a number of different detectors, including an array of diamond-detector leakage-current monitors that were fabricated by Princeton. The system has performed well from the beginning of LHC operations, generating only one false-alarm beam abort when a CERN-provided readout board failed.

The carriage on which some of the BRM diamonds are mounted is also the support structure for the Pixel Luminosity Telescope (PLT), a device being developed by Princeton in collaboration with Rutgers, CERN, and other institutions. The PLT, which is based on diamond detectors read by the same pixel readout chip used in the rest of CMS and will be a dedicated luminosity-measurement device, is expected to come into operation in 2015 when the LHC resumes operation after its ongoing shutdown.

### 4.1.1 Luminosity Measurement and Monitoring

**Personnel:** N. Adam, V. Halyo, J. Hegeman, J. Jones P. Lujan[1], D. Marlow, A. Raval, D. Stickland, and Z. Xie[2]; (Graduate Students) P. Hebda, A. Hunt, T. Lou, J. Werner, A. Żurański

The Princeton group has led the measurement of luminosity in CMS, starting with the development of an online luminosity measuring system based on the hadronic forward calorime-

[1]Mainly supported through V. Halyo Early Career Award
[2]Supported through U.S. CMS Operations Program funds

ter (HF)[3], and continuing with the implementation of offline techniques based on the counting of primary vertices and pixel clusters.

The luminosity system performed very well during data taking in 2010 through early 2013. The system reliably delivers luminosity information in real time during CMS running. The loss of physics data resulting from malfunctioning of the luminosity system has been negligible. The offline luminosity bookkeeping system that was designed and implemented by Princeton personnel was brought into operation in June 2010 and has allowed CMS analysis groups to rapidly determine the luminosities for their samples. Recent calibration runs have established a normalization accuracy of 4%, which is comparable to the theoretical uncertainties on the vector-boson production rates.

The absolute normalizations for the various luminometers employed in CMS methods are determined using a separation scan method pioneered by S. Van der Meer (VdM) at the ISR. In the VdM scan approach, the beam-size parameters are measured by displacing the beams with respect to one another and observing how the luminosity changes. Since the beam intensity parameters can be measured with high accuracy, one can determine an absolute luminosity, which is in turn used to calibrate the luminosity system. Numerous scans have been obtained during the three years of LHC running. The method is accurate to a few percent. Obtaining levels of precision better than that is an active area of investigation.

Another way to establish the luminosity calibration is by measuring the rate for "standard candle" processes such as inclusive $Z \to \ell + \ell-$ production. The cross section for such processes is known to about 2% at the parton level and to better than 5% when uncertainties from parton-distribution functions are taken into account. Work in this area was pioneered by Halyo and her student J. Werner[4] More recently, studies using the $Z \to \mu^+\mu^-$ mode have been carried out by A. Raval. Thus far, the standard-candle luminometers have to date been used as a cross check on the VdM based methods.

### 4.1.2 Searches for Long-Lived States

The Princeton HEP group has undertaken a series of searches for a new topological signature associated with long-lived states decaying to fermions. Several models of new physics predict the existence of massive, long-lived particles that could manifest themselves through their non-prompt decays to jets. Such scenarios arise, for example, in various SUSY models and also in "hidden valley" models. The first such search, which was led by Halyo in collaboration with members from Rutherford and Purdue, is a search for a heavy resonance decaying to long-lived neutral particles decaying into lepton pairs.[5] In that search, the massive resonance was for simplicity taken to be a Higgs boson $H^0$ that subsequently decays to two long-lived, spinless, neutral particles, which then each have a finite branching ratio to decay to dileptons—i.e., $H^0 \to 2X$, $X \to \ell^+\ell^-$.

[3] "The CMS Luminosity Readout System," CMS Internal Note IN-2007-052 (2007)

[4] "Measurements of Inclusive $W/Z$ Production cross sections at CMS and $W/Z$ as a Luminometer," J. Werner for the CMS Collaboration, Lumi Days Workshop at CERN, January 2011; and "Measurement of the Inclusive $Z \to e^+e^-$ Production Cross Section in Proton-Proton Collisions at $\sqrt{s}7$ TeV and $Z \to e^+e^-$ Decays as Standard Candles for Luminosity at the LHC," J. Werner, Ph.D. Thesis, September 2011.

[5] Public results CMS-PAS EXO-11-004.

Marlow and student Żurański and collaborators are working on a variant of this analysis where the long-lived states decay to jets. The search is technically challenging, since most work on the CMS tracking SW has been focussed on prompt tracks. Nonetheless, Zuranski has shown that the CMS tracker is capable of excellent performance for tracks originating far from the IP. At this writing, Żuraśki's search has progressed to the point where the box has been opened, and a paper draft is currently under internal review in CMS.

#### 4.1.3 Operations Program Management

Marlow was named Deputy Operations Program Manager for U.S. CMS in 2007. He devotes about 25% of his time to activities related to this assignment.

## 4.2 Higgs Search, Tracking Efficiency, and Muon Fake Rate

**Personnel:** Lopes Pegna, Mooney, Olsen, Zenz

Olsen's CMS group has included Associate Research Scientist Lopes Pegna, who also worked on the *BABAR* experiment at SLAC, Seth Zenz, who is a Princeton Fellow in Experimental Physics, and graduate student Mooney. Olsen and Lopes Pegna were both named Fellows of the Fermilab Physics Center (LPC) for 2011 and 2012, receiving travel funds and, in the case of Lopes Pegna, half-salary support. Lopes Pegna left Princeton at the end of 2012.

Olsen shifted the bulk of his effort to CMS after stepping down as *BABAR* Physics Coordinator in the fall of 2007, having the primary scientific goal of discovering the existence of the standard model Higgs boson. He immediately identified the search for a low-mass Higgs as an area of opportunity, given the importance of this mass range in light of data from the Tevatron, and the complete lack of a program to study the decay to the challenging $b\bar{b}$ final state in CMS at that time. Olsen formulated a longterm plan to search for $H \to b\bar{b}$, first studying generic QCD heavy-quark production, then focussing on the search on the channel where the Higgs is produced recoiling against a W or Z boson at high momentum (the so-called "boosted Higgs" analysis). This has been the primary focus of his group for the past five years.

For the period 2008-2009 Olsen served as co-leader of the B Physics Group, helping to prepare CMS for first collision data in 2010. During this period, Olsen and Lopes Pegna developed and had approved by CMS two public documents based on simulated data, including a technique to measure B-meson production (CMS-BPH-09-001) using fully reconstructed $B \to J/\psi K$ decays, and an analysis to measure $b\bar{b}$ correlations using a three-muon final state (CMS-BPH-08-004). The B-meson production analysis was turned into the first measurement of exclusive B-hadron production at the LHC in 2010 (published in Phys. Rev. Lett. 106, 112001, 2011). On the detector front, Olsen's groups has been active in the CMS Tracking Group, where he led the effort in 2010 to measure tracking efficiency for muons and hadrons using first collision data (CMS-TRK-10-002), and in the Muon Group mentoring graduate student Mooney on his measurement of muon fake rates (published in JINST 7, P10002, 2012). Zenz works on radiation damage studies for the Pixel Group, as well as on performance studies and as an on-call expert.

Early in 2011 Olsen was asked to lead the newly formed Hbb sub-group of the CMS Higgs PAG, where he initiated an intense effort searching for Higgs-like objects (SM or BSM) decaying to the $b\bar{b}$ final state. This effort led to the first publication of limits on the search for the Higgs boson in this channel at the LHC (Phys. Lett. B710, 284, 2012), in which members of Olsen's group were primary analysts (concentrating on the WH subchannel). This work continued in 2012, culminating in the exciting discovery of a new boson with a mass near 125 GeV in the $H \to \gamma\gamma$ and $H \to ZZ$ channels. Olsen served as one of two co-editors of the discovery paper (Phys. Lett. B716, 30, 2012), and his limits on the search for bottom-quark decays were included in this work. Olsen was soon after announced as the next Co-Leader of the CMS Higgs Group and began his two-year term in January, 2013. This is a challenging time, during which final results on the 7 and 8 TeV data sets will be analyzed and published, followed by preparations for the next run at higher energy. The

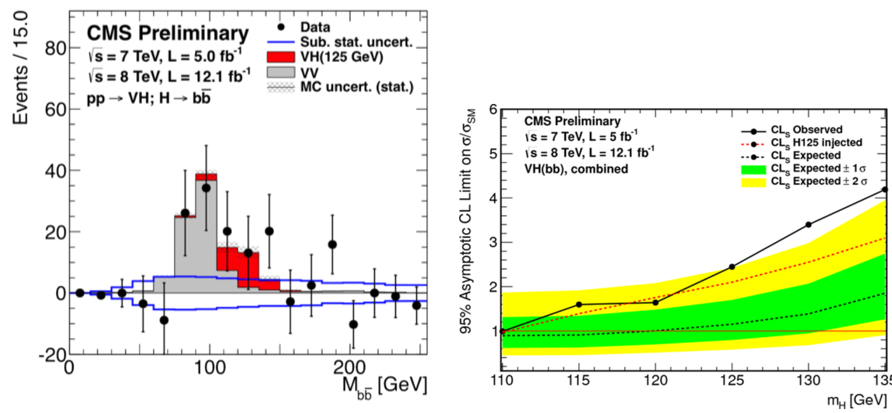


Figure 2: Left: distribution of dijet invariant mass for events in the VHbb search passing a loosely optimzed selection, after background subtraction. Right: 95% confidence level upper limits on standard model Higgs production in the VHbb channel using $17\,\mathrm{fb}^{-1}$ of collision data.

most recent results on the $b\bar{b}$ search were presented at the HCP conference in Novebmer, 2012, and are illustrated in Fig. 2, where the standard model diboson signature, an important calibration for the analysis, is starting to be seen above the background. The final result on the full 2011-2012 dataset is currently under review in CMS and should be published by the beginning of summer. During the period 2010-2012, Olsen has also served as CMS contact to the LHC Higgs Cross Section Working Group, which recently published cross sections for 7 and 14 TeV that are the common reference for all LHC Higgs search results (arXiv:1201.3084; arXiv:1101.0593). Finally, during 2012-2013 Olsen serves as the CMS liason to the Snowmass process, helping to coordinate activities and acting as overall editor of the white paper.

# 5 CMS Experiment at the LHC

## 5.1 SUSY and Lepto-Quark Searches

**Personnel:** C. Tully, (Dicke Fellow) S.-A. Koay, (Graduate Students) E. Berry, T. Medvedeva, E. Laird, H. Saka

The first LHC results on Supersymmetry searches and the first results to achieve a mass reach of 500-650 GeV/c$^2$, significantly above the Tevatron sensitivity, came from the $\alpha_{\mathrm{T}}$ analysis on which Edward Laird is one of the primary analyzers. The strength of the $\alpha_{\mathrm{T}}$-based search is the speed at which missing energy observables can be understood and modeled by data-derived backgrounds. In 2012, the most stringent limits on $1^{st}$ and $2^{nd}$ generation scalar lepto-quark pair production were published in 2012 in *Phys. Rev.* D. This work was primarily authored and coordinated by Edmund Berry. In the $3^{rd}$ generation LQ search, Halil Saka has produced the first analysis of the $t\bar{t}\tau^+\tau^-$ final-state. Edward and Edmund served as Run Field manager for the entire CMS experiment, a position normally held by senior researchers and faculty. Edward was awarded the 2010 Achievement Award for his contributions to the HCAL self-trigger system, a system used to monitor anomalous contributions to the missing energy spectrum from HPD discharging. Edmund was awarded the 2012 Achievement Award for his contributions to the HCAL online data-acquisition operations.

In the fully hadronic SUSY searches, Sue Ann Koay has made major contributions to the first stop pair production results from CMS on the 7 TeV data. During 2012, her work on the jet and transverse missing energy trigger in high pile-up conditions greatly improved the signal efficiencies for the stop signal. This work has lead to her appointment as the 2013-2014 JetMET HLT convener to prepare for 14 TeV trigger menus for all-hadronic SUSY searches.

## 5.2 Higgs-to-$\gamma\gamma$ Search

**Personnel:** C. Tully, (Graduate Student) X. Quan

In 2011-2012, the Princeton group retained sole responsibility for the Higgs di-photon search trigger channels. These do-photon triggers were the basis for the Higgs boson discovery in the $\gamma\gamma$ final state. In late 2010, when Xiaohang Quan and Chris Tully first took on this responsibility, the extrapolation to instantaneous luminosities of $5\times10^{33}$ cm$^{-2}$s$^{-1}$ shows significant efficiency loss and the need to tighten photon $E_{\mathrm{T}}$ thresholds. By keeping isolation cone thresholds loose and making more effective use of local shower shape variables in a combined OR-trigger, the photon $E_{\mathrm{T}}$ thresholds (26/18) were kept at the same low thresholds used in 2011. The trigger efficiency was maintained at greater than 99% for both cut-based and MVA analyses. The evaluation of the trigger efficiencies with $Z \rightarrow e^+e^-$ tag and probe was completed by Xiaohang and included in the Higgs discovery papers.

Xiaohang is collaborating on the Higgs boson mass measurement in the di-photon final-state. Any precision prediction from theory on the branching fractions in the Higgs sector requires a high precision on the Higgs boson mass due to the rapid dependence on the ZZ and WW branching fractions on Higgs boson mass. Xiaohang extended this work to search for additional Higgs bosons that share the di-photon final state.

## 5.3 Calorimeter Upgrades and Detector Operations

**Personnel:** C. Tully, (Dicke Fellow) S.-A. Koay, (Graduate Students) E. Berry, T. Medvedeva, E. Laird, X. Quan, H. Saka, (Undergraduates) N. Jin, R. Meyers

Chris Tully co-lead of the HCAL Upgrade effort and was primary author of the physics performance chapter of the HCAL Upgrade Technical Design Report (TDR) from its beginning in 2008 through the LHCC approval of the project in 2012. The physics chapter contained a set of four collaboration approved analyses on Higgs and SUSY physics with the Upgrade of the hadron calorimeter in 25 ns LHC operation at 14 TeV with a pile-up of 50 events per beam crossing. Chris Tully conducted all pre-approvals, analysis approvals, and wrote the final analysis contributions and responded to the CMS analysis review committee. The analyses were accepted by the LHCC and the Upgrade HCAL TDR was approved by the committee without modification.

The upgrade physics studies required a significant expansion of the particle-flow clustering capabilities of the CMS detector to include longitudinal association of transverse clusters. The performance of the clustering in high pile-up conditions showed significant improvement from timing and longitudinal segmentation, and these improvements were directly reflected in improvements in physics studies at 14 TeV. Figure 3 shows the hit multiplicities in HCAL superclusters for two different pile-up conditions with the current detector, 50 pile-up events with 25 ns spacing and 50 pile-up events with 50 ns spacing, and with the particle flow configured to take full advantage of the HCAL depth segmentation in 50 pile-up event conditions with 25 ns spacing. The anomalous hit count in the endcap clusters indicate the particle flow clustering is failing in that region in a high pile-up environment. The Upgrade PFlow eliminates the anomalous hits in the endcap region and greatly reduces the average hit multiplicity as expected for single pion clusters.

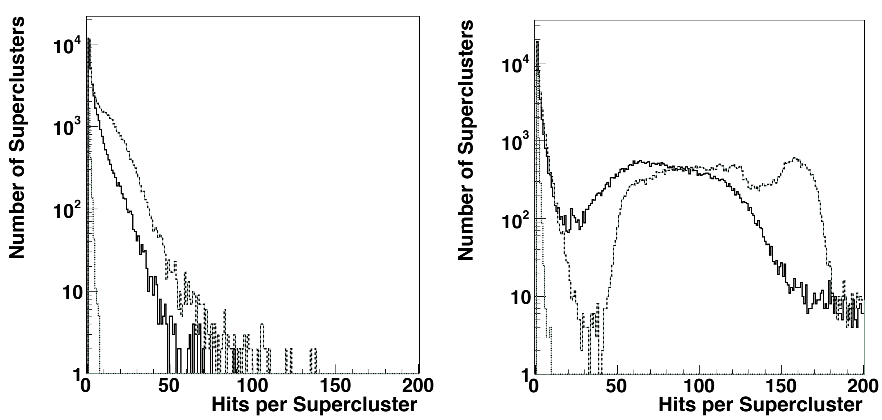


Figure 3: Comparisons of the barrel (left) and endcap (right) hit multiplicites in HCAL superclusters are shown for two different pile-up conditions with the current detector, 50 pile-up events with 25 ns spacing (dotted line) and 50 pile-up events with 50 ns spacing (solid line), and with the particle flow configured to take full advantage of the HCAL depth segmentation (dotted line) in 50 pile-up event conditions with 25 ns spacing.

# 6 BNL E787: Search for $K^+ \to \pi^+\nu\overline{\nu}$

**Personnel:** A. Bazarko, M. Ito, D. Marlow, P. Meyers, F. Shoemaker, A.J.S. Smith (Graduate Students) M. Ardebili, M. Convery, R. McPherson, R .Stone

E787 was founded in 1984 by a Princeton-BNL-TRIUMF collaboration. It continued into the late 1990's, when it became E949 with a greatly expanded collaboration. Princeton did not participate in E949. A large part of the Princeton contribution to E787 occurred prior to the start of this grant in 1992. In particular, Princeton contributed the range stack and barrel veto arrays and the online trigger. Members of the Princeton group led the original analysis and developed many of the techniques that became part of the software infrastructure.

During the period covered by this grant, Princeton was strongly involved in the first major upgrade of the detector, which was done under the E787 designation. Specific contributions included the design and fabrication of an ultra-low-mass straw-tube tracker for the the range stack and an upgraded trigger system. Princeton was also involved in the development of an ultra-low mass inner tracking detector.

Princeton continued to lead the analysis after the upgrade and Princeton students studied both the primary $K^+ \to \pi^+\nu\overline{\nu}$ mode[6] as well $K^+ \to \pi^+\mu^+\mu-$[7], and $K^+ \to \mu^+\nu\gamma$[8]. The flavor-changing-neutral-current (FCNC) $K^+ \to \pi^+\nu\overline{\nu}$ mode is of greatest interest since in the standard model, it can proceed only via higher-order weak diagrams. Since the rate for this process can be reliably computed with the SM (assuming the Kobayashi-Maskawa matrix elements are known), it provides a sensitive probe for possible beyond-the-standard-model contributions. $K^+ \to \pi^+\mu^+\mu-$ is also a FCNC mode, but can proceed via long-distance diagrams that are difficult to calculate precisely.

# References


[1] S. Adler *et al.* [E787 Collaboration], "Search for the decay $K^+ \to \pi^+\pi^0$ neutrino anti-neutrino," Phys. Rev. D **63**, 032004 (2001) [hep-ex/0009055].

[2] S. Adler *et al.* [E787 Collaboration], "Measurement of direct photon emission in $K^+ \to \pi^+\pi^0\gamma$ decay," Phys. Rev. Lett. **85**, 4856 (2000) [hep-ex/0007021].

[3] S. Adler *et al.* [E787 Collaboration], "Measurement of structure dependent $K^+ \to \mu^+\nu\gamma$ decay," Phys. Rev. Lett. **85**, 2256 (2000) [hep-ex/0003019].

[4] S. Adler *et al.* [E787 Collaboration], "Further search for the decay $K^+ \to \pi^+\nu\bar{\nu}$," Phys. Rev. Lett. **84**, 3768 (2000) [hep-ex/0002015].

[5] S. C. Adler *et al.* [E787 Collaboration], "Upper limit on the decay $K^+ \to e^+\nu\mu^+\mu^-$," Phys. Rev. D **58**, 012003 (1998) [hep-ex/9802011].


[6]Ph.D. topic of R. McPherson
[7]Ph.D. topic of M. Ardebili
[8]Ph.D. topic of M. Convery

[6] S. Adler *et al.* [E787 Collaboration], "Evidence for the decay $K^+ \to \pi^+ \nu\bar{\nu}$," Phys. Rev. Lett. **79**, 2204 (1997) [hep-ex/9708031].

[7] S. Adler *et al.* [E787 Collaboration], "Observation of the decay $K^+ \to \pi^+ \mu^+ \mu^-$," Phys. Rev. Lett. **79**, 4756 (1997) [hep-ex/9708012].

[8] P. Kitching *et al.* [E787 Collaboration], "Observation of the decay $K^+ \to \pi^+ \gamma\gamma$," Phys. Rev. Lett. **79**, 4079 (1997) [hep-ex/9708011].

[9] S. C. Adler, M. S. Atiya, I-H. Chiang, J. S. Frank, J. S. Haggerty, T. F. Kycia, K. K. Li and L. S. Littenberg *et al.*, "Search for the decay $K^+ \to \pi^+$ neutrino anti-neutrino," Phys. Rev. Lett. **76**, 1421 (1996) [hep-ex/9510006].

[10] M. S. Atiya, I. H. Chiang, J. S. Frank, E. Garber, J. S. Haggerty, M. Ito, T. F. Kycia and K. K. Li *et al.*, "A detector to search for $K^+ \to \pi^+ \nu\bar{\nu}$," Nucl. Instrum. Meth. A **321**, 129 (1992).

[11] M. S. Atiya, I. H. Chiang, J. S. Frank, J. S. Haggerty, M. M. Ito, T. F. Kycia, K. K. Li and L. S. Littenberg *et al.*, "Search for the decay $\pi^0 \to \gamma X$," Phys. Rev. Lett. **69**, 733 (1992).

# 7 DoE Supported Activities of Prof. K. McDonald 1992-2012

1. **BCD at the SSC.** During the SSC era Prof. McDonald was lead author/editor (together with N.S. Lockyer, now Director of TRIUMF) of the Expression of Interest for a Bottom Collider Detector (BCD) [1]. While the SSC was never completed, the essence of the BCD has been realized as the LHCb experiment. Reports on work related to the BCD by Prof. McDonald in 1992-93 include [2, 3, 4, 5].

2. **Detector Development.** Beginning in the SSC era and continuing to the present, Prof. McDonald has been involved in various detector R&D activities. For the BCD this included studies of straw-tube tracking detectors [6] (which led to the straw-tube tracker built at Princeton for BNL E-787), and CsI photocathodes [7, 8, 9, 10, 11]. In the BaBar era, issues with the lifetime of the Bakelite resistive plate chambers led to studies that continued into the Daya Bay and ILC eras [12, 13, 14, 15]. Around 2000, Prof. McDonald become involved in R&D concept for very large (possibly magnetized) liquid Argon time projection chambers with multiple TPC modules inside a single giant cryostat [16]; this concept has been adopted by the LBNE project.

3. **Accelerator Physics.** In the 1980's Prof. McDonald took on an interest in accelerator physics that remains a major theme of his research to this day. Initially the emphasis was on prospects for laser acceleration, aspects of which was reported in the 90's in [17, 18].

   In 1992, Prof. McDonald attended a workshop in which a prophetic vision of D. Neuffer (Fermilab) from 1980 was re-evaluated: namely, the prospect for colliding rings of muon beams. Such muons beams are much less subject to initial-state radiation (beamstrahlung) that blurs the energy of $e^+e^-$ colliders at the TeV scale, and also couple strongly enough to the Higgs boson that an S-channel muon collider (at $63 \times 63$ GeV) could measure the expected 4-MeV-width of a standard-model Higgs. Prof. McDonald argued in 1992 that it was timely to reconsider the technical merits of muon-based accelerators [19], which led to the formation of the Muon Collider Collaboration in 1997, which transformed into the Muon Accelerator Project (MAP) in 2010 (in which Prof. McDonald is L2 Manager for the Target System).

   In 1998, S. Geer (Fermilab) had the bold vision that the decay of muons in a GeV storage ring would provide a much better source of neutrinos (so-called Neutrino Factory) for long-baseline neutrino-oscillation studies than conventional neutrino beams from pion decay. Since then, R&D towards a Muon Collider has also emphasized a Neutrino Factory.

   Already in 1997 Prof. McDonald began to address the challenges associated with the production of the needed intense muon beams via a multimegaWatt proton beam (with ns-pulse structure as required for a Muon Collider/Neutrino Factory). Survival of the target favors replacing it every pulse, with the target as a (free) liquid metal jet, optimally mercury, all inside a magnetic "bottle" of up to 20 T [20]. This led to an extensive, ongoing R&D program (see [21]) that included two demonstrations experiments, items 4 and 5.

4. **BNL E-951.** BNL experiment E-951 studied the interaction of a primary proton beam with a free mercury jet, and showed that while the mercury jet is disrupted by the proton beam, the disruption is relatively benign [20].

5. **CERN MERIT Experiment.** As a followup to BNL E-951 an experiment was conducted at CERN in which a primary proton beam collided with a free mercury jet inside a 15-T solenoid magnetic field, with single-pulse conditions equivalent to those required for a Muon Collider/Neutrino Factory. The strong magnetic field suppressed the disruption of the mercury jet by the proton beam, and the experiment validated the concept of the mercury jet target for a Muon Collider [22].

6. **SLAC E-144, Strong-Field QED.** In the 1980's Prof. McDonald conceived of a study of electron-positron pair production in collisions of an intense laser beam with photons backscattered from the laser by a high-energy electron beam. In the 1990's this was realized as expt. E-144 at SLAC [23, 24, 25, 26], using a teraWatt laser provided by A. Melissinos *et al.* (U. Rochester). This experiment remains the only successful laboratory study of "sparking the vacuum" via a strong electromagnetic field.

7. BaBar **at SLAC.** Prof. McDonald participated in the BaBar experiment until $\approx$ 2000, with emphasis on design and construction of the drift chamber. The many technical notes from this effort at Princeton can be viewed at [27], and some aspects of these were published in [28, 29]. The Princeton contributions to the BaBar physics analysis are described in the report of Prof. Olsen.

8. **SLAC E-166, Undulator-Based Production of Polarized Positrons.** Prof. McDonald was cospokesperson (together with John Sheppard of SLAC) of a successful demonstration experiment that a beam of positrons with 80% longitudinal polarization (suitable for use at an International Linear Collider) could be produced by first sending a high-energy electron beam through a circularly polarized undulator, and then having the circularly polarized MeV photons interact with a thin tungsten target [30, 31]. This concept is due to A. Mikhailichenko (Cornell), who participated in the experiment.

9. **Daya Bay Reactor Antineutrino Experiment.** Prof. McDonald's interest in a Neutrino Factory (item 3) led him to participate in the Daya Bay Reactor Antineutrino Experiment to measure the value of the neutrino-mixing parameter $\theta_{13}$. Princeton involvement in the detector construction was focused on the gas-handling system for the resistive plate chambers of the muon tagger/veto [32]. The experiment made the first statistically significant measurement of $\theta_{13}$ [33, 34], which has major impact on the coming program to measure CP-violation in the neutrino sector.

10. **Accelerator-Based Neutrino-Oscillation Experiments.** Prof. McDonald has modest, ongoing involvement in the $\mu$BooNE and LBNE experiments at Fermilab, with an interest in future options such as $\nu$STORM and a Neutrino Factory.

A full bibliography of Prof. McDonald's research papers is at [35].

# References


[1] H. Castro *et al.*, *Expression of Interest for a Bottom Collider Detector at the SSC*, submitted to the SSC Lab (May 25, 1990),
http://puhep1.princeton.edu/~mcdonald/papers/bcd_eoi.pdf

[2] K.T. McDonald, *Errors and Dilutions in the Measurement of $CP$ Violation in the $B\bar{B}$ System*, Workshop on $B$ Physics at Proton Accelerators (SSC Lab, June 30, 1992),
http://puhep1.princeton.edu/~mcdonald/papers/mcdonald_ssc_207_92.pdf

[3] K.T. McDonald, *The Forward Arm of a Bottom Collider Detector*, Workshop on $B$ Physics at Hadron Colliers (SSC Lab, Sept. 25, 1992),
http://puhep1.princeton.edu/~mcdonald/papers/mcdonald_ssc_92.pdf

[4] K.T. McDonald, *Vertex Detectors for B Physics at the SSC*, SSC Science Symposium (Madison, WI, Mar. 30, 1993),
http://puhep1.princeton.edu/~mcdonald/bphys/btrans_033093.pdf

[5] K.T. McDonald and J.D. Bjorken, *Proposal for a Feasibility Study of Very Large Aperture Quadrupole Magnets*, (Apr. 1993), Workshop on Physics at Current Accelerators and the Supercollider (ANL, June 2-5, 1993),
http://puhep1.princeton.edu/~mcdonald/papers/bjorken_slac-pub-6138.pdf

[6] W.S. Anderson *et al.*, *Electron Attachment, Effective Ionization Coefficient, and Electron Drift Velocity for $CF_4$ Gas Mixtures*, Nucl. Instr. and Meth. **A323**, 273 (1992).

[7] N.S. Lockyer *et al.*, *Observation of Čerenkov Rings Using a Low-Pressure Parallel-Plate Chamber and a Solid Cesium-Iodide Photocathode*, Nucl. Instr. and Meth. **A332**, 142 (1993).

[8] C. Lu, K.T. McDonald and Y. Zhu, *Helium Gas Mixtures for Ring Imaging Čerenkov Detectors with CsI Photocathodes*, Nucl. Instr. and Meth. **A334**, 328 (1993).

[9] C. Lu and K.T. McDonald, *Properties of Reflective and Semitransparent CsI Photocathodes*, Nucl. Instr. and Meth. **A343**, 135 (1994).

[10] C. Lu *et al.*, *Characterization of CsI Photocathodes for Use in a Fast RICH Detector*, Nucl. Instr. and Meth. **A366**, 60 (1995).

[11] C. Lu *et al.*, *Prototype Studies of a Fast RICH Detector with a CsI Photocathode*, Nucl. Instr. and Meth. **A371**, 155 (1996)

[12] C. Lu, *RPC electrode material study*, Nucl. Instr. and Meth. **A602**, 761 (2009).

[13] C. Lu *et al.*, *Aging Study of RPCs for the SiD Hcal and Muon System* (June 8, 2010),
http://puhep1.princeton.edu/~mcdonald/examples/detectors/lu_arxiv_1006.1061.pdf

[14] C. Lu, K.T. McDonald and A.J.S. Smith) *Microscope Study of BESIII-type RPC Aging Phenomena* (Sep. 8, 2011),
http://puhep1.princeton.edu/~mcdonald/dayabay/Lu/MicroscopeStudyOfAging.pdf

[15] C. Lu *et al.*, *Aging study for the BESIII-type RPC*, Nucl. Instr. and Meth. A **661**, S226 (2012),

[16] D.B. Cline *et al.*, *LANNDD – a massive liquid argon detector for proton decay, supernova and solar neutrino studies and a neutrino factory*, Nucl. Instr. and Meth. A **503**, 136 (2003).

[17] K.T. McDonald, *Comment on "Experimental Observation of Electrons Accelerated in Vacuum to Relativistic Energies by a High-Energy Laser" by Malka et al.*, Phys. Rev. Lett. **80**, 1350 (1998).

[18] K.T. McDonald and K. Shmakov. *Temporary Acceleration of Electrons While Inside an Intense Electromagnetic Pulse*, Phys. Rev. ST Accel. Beams **2**, 121301 (1999).

[19] P. Chen and K.T. McDonald, *Summary of the Physics Opportunities Working Group*, A.I.P. Conf. Proc. **279**, 853 (1992).

[20] A. Hassanein *et al.*, *An R&D program for targetry and capture at a neutrino factory and muon collider source*, Nucl. Instr. and Meth. **A503**, 70 (2003).

[21] *Muon Collider Targetry and Phase Rotation*, MuonColliderTargetryandPhaseRotation

[22] K.T. McDonald *et al.*, *The MERIT High-Power Target Experiment at the CERN PS*, PAC09 (Vancouver, May 5, 2009),
http://www.hep.princeton.edu/~mcdonald/mumu/target/pac09/tu4gri03.pdf

[23] C. Bula *et al.*, *Observation of Nonlinear Effects in Compton Scattering*, Phys. Rev. Lett. **76**, 3116 (1996).

[24] T. Kotseroglou *et al.*, *Picosecond Timing of Terawatt Laser Pulses with the SLAC 46-GeV Electron Beam*, Nucl. Instr. and Meth. **A383**, 309 (1996).

[25] D.L. Burke *et al.*. *Positron Production in Multiphoton Light-by-Light Scattering*, Phys. Rev. Lett. **79**, 1626 (1997).

[26] C. Bamber *et al.*, *Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses*, Phys. Rev. D **60**, 092004 (1999).

[27] *Princeton/*BaBar *Drift Chamber Technical Notes*,
http://puhep1.princeton.edu/~mcdonald/tndc/Princeton.html

[28] A. Boucham *et al.*, *The* BABAR *drift chamber project*, Nucl. Instr. and Meth. **A409**, 46 (1998).

[29] G. Sciolla *et al.*, *The* BABAR *drift chamber*, Nucl. Instr. and Meth. **A419**, 310 (1998).

[30] G. Alexander *et al.*, *Observation of Polarized Positrons from an Undulator-Based Source*, Phys. Rev. Lett. **100**, 210801 (2008).

[31] G. Alexander *et al.*, *Undulator-based production of polarized positrons*, Nucl. Instr. and Meth. **A610**, 451 (2009).

[32] C. Lu and K.T. McDonald, *Daya Bay RPC Gas System: Design Report* (July 28, 2007), http://puhep1.princeton.edu/~mcdonald/dayabay/Lu/GasSystemReport.pdf

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

[34] F.P. An *et al.*, *Improved Measurement of Electron Antineutrino Disappearance at Daya Bay*, Chinese Phys. C **37**, 011001 (2013).

[35] *Publications of Kirk T. McDonald*, http://puhep1.princeton.edu/~mcdonald/tex/bib.pdf

# 8 L3 Experiment at LEP

**Personnel:** P. Denes, P. Piroué, C. Tully, D. Stickland, R. Sumner, (Graduate Students) P. Caret, W. Fisher, J. Mans

Many landmark contributions to the understanding of the laws of physics and properties of the universe were established from high precision electroweak measurements on the Z peak. The bulk of the Z bosons at LEP were produced in 1994 and 1995, roughly $10^6$ Z bosons per LEP experiment. The Princeton group was the primary institution responsible for the readout of the BGO crystal electromagnetic calorimeter. This was the highest resolution calorimeter at LEP and established a precedence for crystal calorimetry that led to the CMS electromagnetic calorimeter with PbWO crystals.

The scan of the Z line shape with high precision knowledge of the beam energy, known to 5 MeV, was a powerful tool to measure the Z boson mass and width to 5 MeV, and to count the number of light neutrino families. The 5 MeV measurement precision on the Z width continues to be one of the most powerful constraints on new physics. Similarly, constraints on the weak mixing angle, the strong coupling constant for event shape variables, and the fine structure constant at the Z peak were all essential components to the precision electroweak fit. By the end of 1994, the constraint on the top quark mass was well determined and agree with the later discovery at the Tevatron with the direct production of top quark pairs in 1995.

To push beyond top quark sensitivity to the Higgs boson a comprehensive program of precision measurements was completed. The polarization of tau leptons for Z decay provided a high precision constraint on the weak mixing angle. The measurements of Rb probed new physics in the third generation. The increase in center-of-mass energy to 161 GeV provide a precision W boson pair production threshold scan. That scan combined with 183 GeV and 189 GeV data was used to measure the W mass to 50 MeV. The W boson mass combined with the top quark mass at the Tevatron and the Z peak electroweak fits provided indirect constraints on the Higgs boson mass constraining it to be less than approximately 250 GeV, which was later tightened to an upper limit of 154 GeV before the Higgs boson discovery at the LHC.

The Higgs boson was actively searched for in the LEP data from 189 GeV to 209 GeV through the completing of data-taking in 2000. The Higgs boson search limit was pushed to 114.4 GeV and provided an important lower bound on the search in the LHC era where low mass searches would not have been possible. The Princeton group has an important role in combining the Higgs boson search data across all four LEP experiments to achieve this ultimate sensitivity. The final Higgs boson search data is shown in Figure **??**. The Princeton group had important leadership responsibilities in the L3 experiment. Prof. Tully served as the Higgs group convener in 1999-2001. Some of the analyses that Princeton completed during this period include the measurement of ZZ production in the all hadronic final state. The measured cross sections are plotted in Figure 4.

Prof. Tully was Run Coordinator for the L3 experiment for several important data-taking periods in 2000. Throughout the period of operation of the BGO calorimeter, the percentage of working, calibrated channels was maintained at above 98% at the level of the

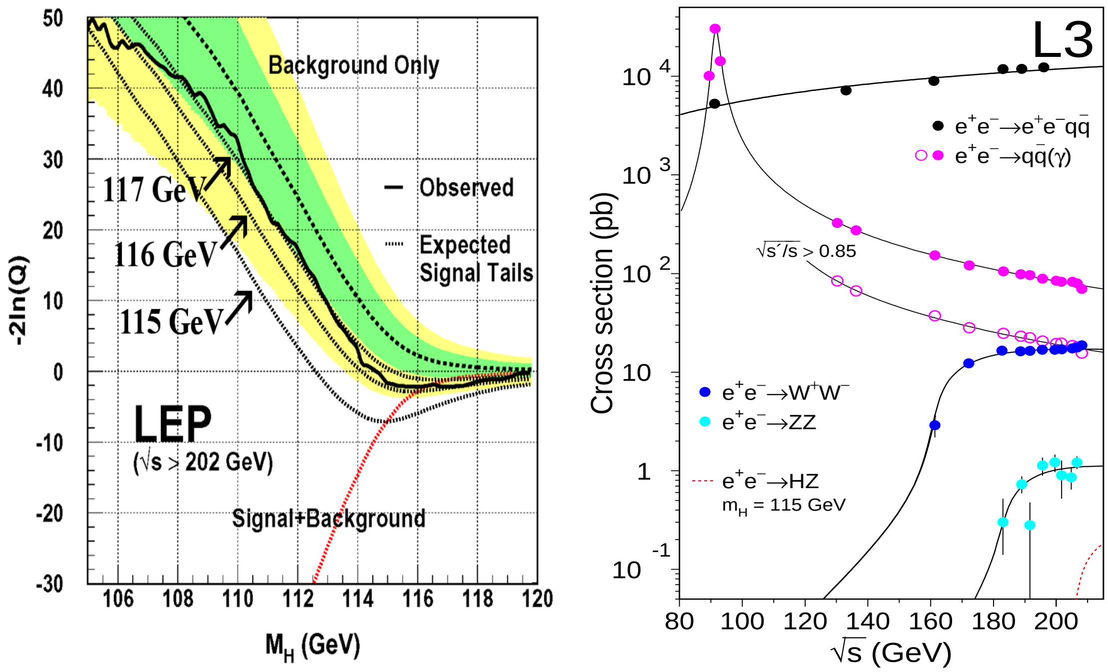


Figure 4: On the left is the high energy LEP data showing an observed rate that is compatible within 2 standard deviations of the background up through 115 GeV where the search sensitivity was limited by the LEP beam energy. On the right is a compilation of cross section measurements from the Z peak through the highest energy operation, including the measurement of ZZ production.

as-installed failures of photodetectors. There were periods in 1994 and 1995 where groups of 60 channels, a readout box, would fall out of the readout, and there were difficulties with correlated noise in the BGO immediately after the installation of the new silicon tracker detectors for vertex reconstruction. However, the Princeton group with it's decade long dedication to excellent in the BGO calorimeter repaired the readout, improved the grounding, and provided offline noise decorrelation algorithms based on unsprayed channels. Online monitoring tools provided quick feedback on the status of the noise, temperature conditions, and Xenon flasher data. Princeton in collaboration with Caltech also provided calibration data through dedicated RFQ calibrations using 17 MeV photons from a low energy $H^-$ accelerator. Despite the low statistics of Bhabha scattering in high energy operation, most of which came from dedicated short runs on the Z peak, the energy calibration on the BGO maintained a constant term of 1% throughout the decade of operation, providing unique high energy resolution calorimetry in the LEP era.

The graduate students in this group, including Prof. Tully from 1992, are all physics professors at this time. Prof. Mans at the University of Minnesota, and Prof. Fisher at Michigan State University. A list of L3 publications can be found at URL: http://l3.web.cern.ch/l3/paper/publications.html

# 9 MiniBooNE: Medium-Baseline Neutrino Oscillation Search at Fermilab

**Personnel:** Faculty – A.O. Bazarko, P.D. Meyers, F.C. Shoemaker; Engineer –W. Sands; Postdoc – H. Tanaka; Graduate student – R. Patterson

The Princeton high-energy physics group was a key part of the Fermilab Booster Neutrino Experiment ("MiniBooNE," Experiment 898) at Fermilab. MiniBooNE is a single-detector neutrino experiment looking for evidence for $\nu_\mu$ oscillations, primarily in the $\nu_e$ appearance channel. Specifically, the experiment was designed to confirm or rule out definitively the signal presented by LSND. The region of $\Delta m^2 \approx 1$ eV$^2$ and small $\sin^2 2\theta$ favored by LSND is well away from the regions allowed by atmospheric and solar neutrino studies (which are, in turn, well away from each other). The 3-neutrino-mixing model does not have room for such a new mass difference, and thus incorporating the LSND result would require a new neutrino type, a "sterile" state to be consistent with the limit on active species from the $Z$ width. This would be new physics, well beyond the Standard Model, and thus of great interest.

The experiment consists of a $\sim 0.5$-1-GeV neutrino beam produced by 8 GeV protons from the Booster and a detector located 500 m from the production target. The detector[9] is a 40-foot-diameter spherical tank filled with 800 tons of mineral oil. It sits in a cylindrical vault and is topped with a concrete enclosure for electronics and services and an earth berm to reduce cosmic rays to manageable levels. The tank is divided into a main volume and a veto region (the latter being the outer 35 cm of the sphere), both instrumented with 8-inch photomultiplier tubes (PMTs). Charged particles passing through the oil produce Čerenkov light, as well as a small amount of scintillation light. The spatial pattern of the light and its time distribution allow reconstruction of neutrino-induced events and distinction between final-state muons, $\pi^0$'s, and electrons.

Princeton joined MiniBooNE in 1998, early enough to play a big part in the design and construction of the detector and in the data-taking and analysis, remaining active through 2007, when the first oscillation analysis was published.

## 9.1 Princeton design and construction tasks in MiniBooNE

The Princeton High Energy Physics Group designed the Phototube Support Structure (PSS), a device that consists of the optical barrier separating the main tank from the veto, the structure that mounts it to the inside of the tank, 1520 8″ photomultiplier tubes and their mounting hardware, the cable plant that powers the tubes and carries their signals, and, with Los Alamos, the plumbing for filling the tank with oil and controlling its temperature. (This is basically everything inside the tank except for some calibration equipment.) This project also included the scaffolding needed to install the PSS in an efficient and safe manner. The engineering, fabrication, and assembly capabilities of Princeton's Elementary Particles Laboratory allowed us to take on this important task. Specifically, engineer William Sands

[9] A.A. Aguilar-Arevalo *et al.*, "The MiniBooNE Detector," Nucl. Instr. Meth. A **599**, 28 (2009).

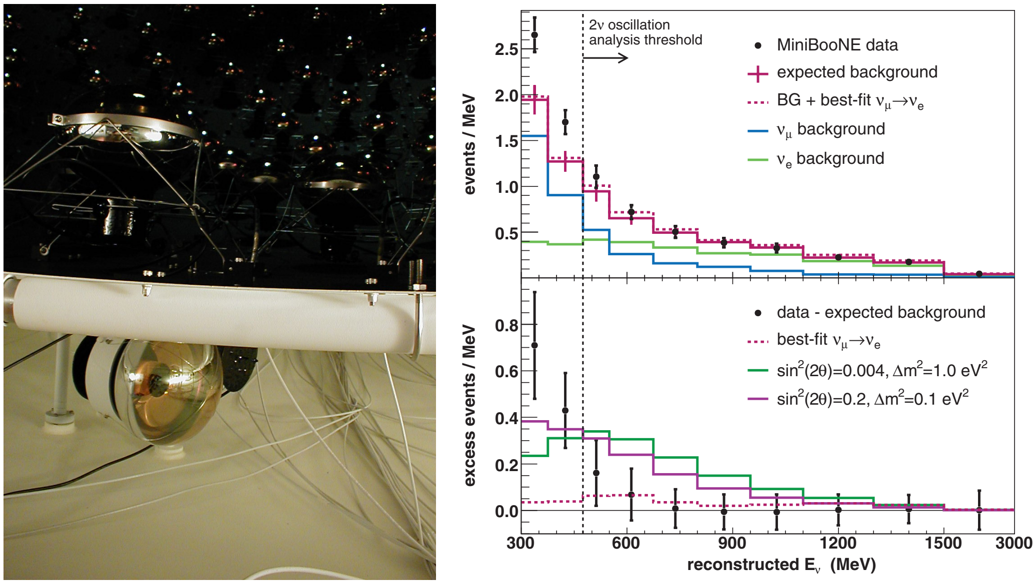


Figure 5: Left: the MiniBooNE detector. Right: First oscillation results, showing no evidence for $\nu_\mu \rightarrow \nu_e$ oscillations, but a low-energy excess of electron-like events.

lead the design effort, as well as coordinating the prototyping and fabrication of the PSS, and our machinists and technicians allowed us to follow through with the fabrication and installation. We also aided other collaborating groups in the design and fabrication of their hardware projects.

The Princeton group also led the installation of the cabling and all the in-tank equipment. Figure 5 shows the MiniBooNE detector in a late phase of construction. The veto region must be white to maximize light collection, the main tank black to minimize reflections that would confound event reconstruction. The choice of surface coatings and other PSS materials that must be compatible with mineral oil was the subject of R&D work at Princeton. The installation took from January to October of 2001.

## 9.2 Data and analysis

MiniBooNE collected neutrino data from 2002 to 2007. The Princeton group was a leader in the analysis as well. Tasks that were performed primarily by the Princeton group included the online data monitoring, the PMT calibration, the detector Monte Carlo simulation including the very difficult modeling of the optical properties of the detector, aspects of the beam modeling, and much of the error analysis. Ultimately the collaboration developed two rather independent analyses, with separate event reconstruction. One of these was developed entirely at Princeton, and this was the result the collaboration chose to publish.[10] In this analysis, the energy region $475 < E_\nu < 1200$ MeV had an insignificant excess of

[10]A.A. Aguilar-Arevalo *et al.*, "Search for Electron Neutrino Appearance at the $\Delta m^2 \sim 1$ eV$^2$ Scale," Phys. Rev. Lett. **98**, 231801 (2007).

$22 \pm 19^{stat} \pm 35^{sys}$ events over the predicted background – see Fig. 5. The best-fit 2-$\nu$ oscillation parameters were below the LSND region and consistent with no oscillations. There was a substantial excess of observed events over the expected background below the oscillation search region. In the months following the first result, the Princeton group investigated possible backgrounds in this region and found that 25-30% of the excess was explained by conventional backgrounds not present in our simulations. The remaining excess is the subject of continued study. MiniBooNE has continued to take data, notably in antineutrino mode. The Princeton group has not been involved in this, but the calibration, reconstruction, and Monte Carlo programs we developed are still used in all MiniBooNE analyses.

**Princeton MiniBooNE Publications 2007-2012**


1. "Search for Electron Neutrino Appearance at the $\Delta m^2 \sim 1$ eV$^2$ Scale," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. **98**, 231801 (2007).

2. "Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. **100**, 032301 (2008).

3. "First observation of coherent $\pi^0$ production in neutrino-nucleus interactions with $E_\nu <$ 2 GeV," A.A. Aguilar-Arevalo *et al.*, Phys. Lett. B **664**, 41 (2008).

4. "Compatibility of high-$\Delta m^2$ $\nu_e$ and $\overline{\nu}_e$ neutrino oscillation searches," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. **D78**, 012007 (2008).

5. "The MiniBooNE Detector," A.A. Aguilar-Arevalo *et al.*, Nucl. Instr. Meth. A **599**, 28 (2009).

6. "Unexplained Excess of Electronlike Events from a 1-GeV Neutrino Beam," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. **102**, 101802 (2009).

7. "Neutrino flux prediction at MiniBooNE," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. **D79**, 072002 (2009).

8. "Measurement of $\nu_\mu$ and $\nu_e$ Events in an Off-Axis Horn-Focused Neutrino Beam," P. Adamson *et al.*, Phys. Rev. Lett. **102**, 211801 (2009).

9. "Search for Muon Neutrino and Antineutrino Disappearance in MiniBooNE," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. **103**, 061802 (2009).

10. "Measurement of the ratio of the $\nu_\mu$ charged-current single-pion production to quasielastic scattering with a 0.8 GeV neutrino beam on mineral oil," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. **103**, 081801 (2009).

11. "The extended-track event reconstruction for MiniBooNE," R.B. Patterson *et al.*, Nucl. Instr. Meth. A **608**, 206 (2009).

12. "A Search for Core-Collapse Supernovae using the MiniBooNE Neutrino Detector," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. **D81**, 032001 (2010).

13. "Measurement of $\nu_\mu$ and $\bar{\nu}_\mu$ induced neutral current single $\pi^0$ production cross sections on mineral oil at $E_\nu \sim \mathcal{O}$ (1 GeV)," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. **D81**, 013005 (2010).

14. "First measurement of the muon neutrino charged current quasielastic double differential cross section," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. **D81**, 092005 (2010).

15. "Measurement of the neutrino neutral-current elastic differential cross section on mineral oil at $E_\nu \sim 1$ GeV," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. **D82**, 092005 (2010).

16. "Measurement of $\nu$-induced charged-current neutral pion production cross sections on mineral oil at $E_\nu \in 0.5 - 2.0$ GeV," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. **D83**, 052009 (2011).

17. "Measurement of Neutrino-Induced Charged-Current Charged Pion Production Cross Sections on Mineral Oil at $E_\nu \sim 1$ GeV," A.A. Aguilar-Arevalo *et al.*, Phys. Rev. **D83**, 052007 (2011).

18. "Dual Baseline Search for muon neutrino disappearance at $0.5\ \mathrm{eV}^2 < \Delta m^2 < 40\ \mathrm{eV}^2$," K.B.M. Mahn *et al.*, Phys. Rev. **D85**, 032007 (2012).

# 10 DarkSide: Direct WIMP-Dark Matter Searches Using Liquid Argon TPCs

**Personnel:** Faculty – P.D. Meyers, Engineer –W. Sands; Postdocs – L. Grandi, A. Wright; Graduate students – J. Brodsky, G. Koh

In 2007, Meyers began collaborating with the NSF-funded Princeton Particle Astrophysics Group (Profs. Calaprice and Galbiati), developing the two-phase argon Time Projection Chamber (TPC) as an apparatus for direct laboratory searches for Weakly Interacting Massive Particles (WIMPs), a leading dark matter candidate. Initially, we worked with small prototype liquid argon (LAr) scintillation detectors. This effort grew into the DarkSide program, which is now about to commission its first experiment, DarkSide-50, in Gran Sasso National Laboratory (LNGS) in Italy. DarkSide is now an international collaboration led by the Princeton group.

An ultra-low-background experiment like a direct WIMP search at the current state of the art requires a large underground infrastructure of active and passive shielding. For the current and next generation of detectors in the DarkSide program, the shielding facility is a new liquid-scintillator neutron veto, built by the DarkSide collaboration, inside the Borexino Counting Test Facility water tank in Hall C of LNGS.

The Princeton HEP group has focussed its DarkSide activity on the TPC itself. We built and operated DarkSide's first TPC, a 10-kg prototype called DarkSide-10, for several years. We have also led the design and construction of the TPC for DarkSide-50, with 50 kg of active LAr (33 kg fiducial). DarkSide-50 is now entering the commissioning phase for a 3-year physics run. We are also involved in R&D for larger ("Generation 2") experiments.

## 10.1 DarkSide-10

The Princeton HEP group was responsible for the design and construction of DarkSide-10. DS-10 was designed in parallel with the conceptual planning for larger detectors and was intended to test features proposed for DS-50 and beyond. This detector shared many aspects of the DS-50 design, such as the method for creation and maintenance of the gas bubble at the top of the sensitive volume, photosensors operating in liquid argon, ITO-coated windows for the cathode and anode, and TPB layers on the windows and side reflector. The top and bottom windows were each viewed by seven 3" Hamamatsu R11065 PMTs, the predecessors to the R11065-20s being deployed in DarkSide-50.

DS-10 had two long runs in Princeton, March-July 2010 and November 2010-February 2011, and then two long runs in a simple water-and-polyethylene shield underground in LNGS, July-December 2011 and February 2012-February 2013. This is approximately 700 days of cold operations. Accomplishments with DarkSide-10 included: 1) Extended experience in operating the Hamamatsu R11065 PMTs at liquid argon temperature. Generally good performance was observed, but there were problems with the early tubes, and we have been working with Hamamatsu to resolve these. 2) The system for forming and maintaining gas pocket at the top of the sensitive volume worked flawlessly and with excellent stability.

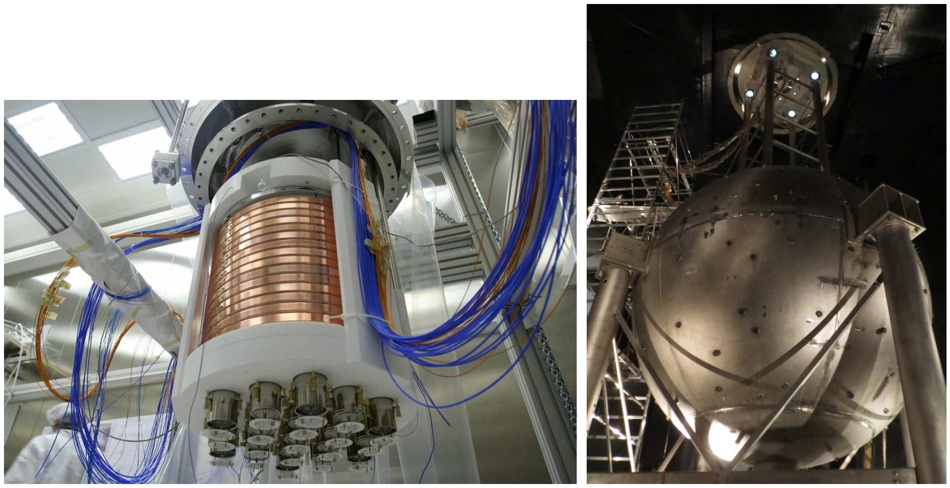

Figure 6: The DarkSide-50 TPC (left), which will be deployed in the liquid-scintillator neutron veto (right), which is in turn in the CTF water tank/muon veto in LNGS.

3) The performance of the ITO layers on the top and bottom windows was good and confirmed that this innovative scheme can be used to close the field lines between anode and cathode, replacing the standard scheme of grids. The light absorption in the ITO led us to minimize its thickness in later deployments and in DarkSide-50. 4) We achieved a light yield of 8.9 photoelectrons/keV$_{ee}$ at null electric field with the gas pocket present, the highest obtained so far with an argon-based detector.[11] 5) We recorded and analyzed two-phase data, clearly observing the S1 (primary scintillation) and S2 (secondary scintillation from drifted electrons) signals. Studies of pulse shape and S2/S1 discrimination between signal-like nuclear recoils and electromagnetic backgrounds show the power of this technology for background rejection.

## 10.2 DarkSide-50

The DS-50 TPC, shown during assembly in Fig. 6 (left), is contained in a stainless steel cryostat that is supported at the center of the liquid-scintillator neutron veto, shown in Fig. 6 (right). The liquid argon is contained in a cylindrical container viewed by thirty-eight 3” Hamamatsu low-background R11065-20 PMTs, nineteen each on the top and the bottom, which view the active LAr through fused silica windows. The cylindrical surface is a reflector that is coated with a wavelength shifter that absorbs the 128-nm scintillation photons emitted by liquid argon and re-emits visible photons that are reflected with high efficiency. The windows at the top and bottom of the cylinder are also coated with the wavelength shifter on the inner surfaces, and on both surfaces with transparent ITO conductive layers. This allows the inner window surfaces to serve as the grounded anode (top)/−HV cathode (bottom) of the TPC while maintaining their outer surfaces at the average PMT photocathode potential.

[11] D. Akimov *et al.*, “Light Yield in DarkSide-10: a Prototype Two-phase Liquid Argon TPC for Dark Matter Searches,” arXiv:1204.6218 (2012).

The fused silica anode window has a cylindrical rim extending downward to form the "diving bell" holding the 1-cm-thick gas layer of the TPC. As in DS-10, the electron drift system consists of the ITO cathode and anode planes, a field cage, and a grid that separates the drift and electron extraction regions. A high voltage is applied between the cathode and grid to produce a vertical electric field to drift the ionization electrons upward. Copper rings outside the cylindrical wall at graded potentials make the drift field uniform throughout the active volume. An independently-adjustable potential between the grid and anode creates the fields that extract the electrons into the gas and accelerate them to create the secondary scintillation signal.

The Princeton HEP group led the design and fabrication of the DS-50 TPC, prototyping new concepts as needed. Unlike the prototypes, DS-50 required painstaking attention to the radio-purity of all the construction materials, limiting air exposure to avoid radon daughters, and extreme cleanliness during assembly.

After the commissioning phase, we anticipate running DS-50 for 3 years. Our background simulations project that this run will have much less than one background event from all sources, yielding a sensitivity to the WIMP-nucleon cross section of $1 \times 10^{-45}$ cm$^2$ at WIMP masses near 100 GeV.

# 11 Research of S. Gubser

**Personnel:** S. Gubser (faculty), J. Ren (graduate student), T. Dumitrescu (graduate student advised by N. Seiberg)

Work of S. Gubser has focused on five main themes: numerical relativity in anti-de Sitter space, non-equilibrium field theory, holographic Fermi surfaces, the phase diagram of QCD and of charged black holes, and conformal symmetries in heavy ion collisions. Progress on each of these topics will be treated in turn below.

Work of T. Dumitrescu has been supervised by N. Seiberg at the Institute of Advanced Study, but funded under the Princeton University DOE grant. It is briefly summarized at the end of this section.

## 11.1 Numerical relativity in anti-de Sitter space

Gubser worked with F. Pretorius and H. Bantilan on numerical finite-difference methods for solving Einstein's equations in asymptotically anti-de Sitter spacetimes. The gauge-string duality maps a class of strongly coupled field theories onto classical gravity with a negative cosmological constant; however, many interesting time-dependent phenomena remain relatively unexplored because they correspond to complicated, evolving geometries, often with causal horizons. For example, one can study black hole formation and ring-down, corresponding to rapid thermalization in the dual field theory, and classical black hole instabilities, corresponding to any of several symmetry-breaking mechanisms in field theory.

The results of Gubser's efforts in this direction during the lifetime of the grant is a paper with F. Pretorius and H. Bantilan[12] in which non-linear ring-down of a black hole in global anti-de Sitter spacetime is studied. The initial data is characterized by highly distorted apparent horizon geometries, dual to a highly compressed fluid on the boundary of global anti-de Sitter space. This highly compressed fluid is reminiscent of the early-time state of a heavy ion collision in the hydrodynamical Landau model. An important punchline of the numerical work in anti-de Sitter space is that the dual fluid very nearly obeys hydrodynamical constitutive relations throughout its evolution. This is in contrast to mainstream thought about the time evolution of a heavy ion collision, in which there is thought to be a period of thermalization during which the stress tensor has no reason to be hydrodynamical. The take-away message is that the gauge-string duality provides an existence proof that a close relative of the Landau model can be embedded into a UV complete theory, albeit a strongly coupled one.

## 11.2 Non-equilibrium field theory

A widely studied aspect of early-time cosmology is the so-called Kibble mechanism, in which a high-temperature, symmetry-restored phase goes through a phase transition to an ordered

[12] H. Bantilan, S. Gubser, and F. Pretorius, *Simulation of Asymptotically $AdS_5$ Spacetimes with a Generalized Harmonic Evolution Scheme*, Phys. Rev. **D85**, 084038 (2012).

phase and produces some density of topological defects (for example, cosmic strings) in the process. This mechanism was later studied by Zurek in a condensed matter context. Although the Kibble-Zurek mechanism is decades old, the treatment of the freezeout process in real time still relies primarily on the sudden approximation introduced by the original authors. Another interesting regime is when the passage through the phase transition is slow. There are then two competing timescales: one describing the rate at which the temperature (or some other control parameter) changes, and another characterizing the response time of the system, which typically diverges at a second order transition. Gubser and collaborators developed a general scaling theory to describe how the effects of these two timescales compete. It is a generalization to out-of-equilibrium field theories of the standard theory of critical exponents near a second order transition, and it constrains real-time Green's functions. Published results to date[13] lay out the general theory and work through several examples, mostly in free field theory.

## 11.3 Holographic Fermi surfaces

With collaborators O. DeWolfe and C. Rosen, Gubser showed that holographic Fermi surfaces can be embedded into string theory. Previous constructions with a similar goal used test branes, which complicates the dual field theory. The dual field theory in the work of Gubser and collaborators[14] is straightforward $\mathcal{N} = 4$ super-Yang-Mills theory at a finite chemical potential. This sharpens questions about zero-point entropy and the role of charged scalars. To help clarify the scalars' role, an example was studied in which the scalars have a well-defined expectation value and hard-gapped $s$-wave superconductivity results. For bulk configurations close to this hard-gapped superconductor, a small holographic Fermi surface develops which exhibits marginal Fermi liquid behavior. Altogether, this line of work brings genuine string theory constructions much closer to interesting questions in condensed matter physics, such as how and whether strong interactions and quasi-particles can co-exist near a Fermi surface.

Gubser has also worked on bottom-up constructions of holographic Fermi surfaces, in which one picks bulk lagrangians with particularly favorable properties. With student J. Ren he showed that one of the entropy-free string theoretic black holes allows for a surprisingly comprehensive analytic treatment of Fermi surfaces based on a minimally coupled Dirac fermion. All wave-functions can be found explicitly, and the Fermi surfaces are evenly spaced in momentum space, with closed-form expressions for their scaling exponents.

## 11.4 The phase diagram of QCD and of charged black holes

A prominent feature expected in the QCD phase diagram is a line of first order phase transitions in the plane of temperature ($T$) and baryon chemical potential ($\mu$), well above

[13] A. Chandran, A. Erez, S. Gubser, and S. Sondhi, *The Kibble-Zurek Problem: Universality and the Scaling Limit,* Phys. Rev. **B86**, 064304 (2012).

[14] O. DeWolfe, S. Gubser, and C. Rosen, *Fermi surfaces in N=4 Super-Yang-Mills theory,* Phys. Rev. **D86**, 106002 (2012).

the known liquid-gas coexistence line of nuclear matter. This line is thought to terminate in a critical point at finite chemical potential, so that the QCD phase transition is a cross-over.

While phase transitions of strongly coupled gauge theories have been explored since the inception of the AdS/CFT correspondence, only recently was it shown, by Gubser in collaboration with DeWolfe and Rosen, that a similar first order line can be found in the $T$-$\mu$ plane, terminating in a critical endpoint at finite $\mu$.[15] Finite $\mu$ corresponds to studying charged black holes in anti-de Sitter space. Unlike in most previous approaches, both sides of the first-order line are described by black holes. Because black holes intrinsically have $\mathcal{O}(N^2)$ degrees of freedom in large $N$ gauge theories, one cannot trust the black hole constructions too far away in the $(T, \mu)$ plane from where a cross-over to the high-temperature, deconfined phase occurs. This limitation doesn't preclude the opportunity to study the nature of the critical endpoint. Indeed, transport coefficients were studied in the vicinity of the critical endpoint,[16] and it was shown that bulk viscosity and conductivity remain finite, but their derivatives with respect to intensive thermodynamic variables diverge. This work complements earlier work of Gubser with students,[17] where the bulk viscosity was studied at zero chemical potential and shown to have a peak near the cross-over. The peak is much less sharp than suggested based on sum-rule arguments.[18] Gubser's black hole calculations eventually helped inform the choice of bulk viscosity in a hydrodynamic study of the quark-gluon plasma by H. Song and U. Heinz.[19]

## 11.5 Conformal symmetry in heavy ion collisions

With A. Yarom and S. Pufu, Gubser established methods for finding trapped surfaces in collisions of shock waves in anti-de Sitter space.[20,21] It was noted by Gubser and his collaborators that an $SO(3)$ subgroup of the conformal group is preserved by the head-on collisions, and that an $SO(2)$ subgroup is preserved by the off-center collisions. These symmetries are quite natural from the point of view of $AdS_5$, but they have not been much studied as symmetries of collisions in dual strongly coupled conformal field theories. Gubser therefore embarked on a program of research to understand the significance of the $SO(3)$ symmetry. First he showed that $SO(3)$, coupled with boost-invariance, leads to new analytic solutions of hydrodynamics.[22] As compared to Bjorken flow and Landau-Khalatnikov flow, the $SO(3)$-symmetric flow has two phenomenologically desirable features: namely, the medium has finite transverse size, and there is radial flow outward in the transverse plane, as well as longitudinal expansion along the beamline directions. Although the discovery of this solution was inspired by string theory constructions, it in no way depends upon them,

[15] O. DeWolfe, S. Gubser, and C. Rosen, Phys. Rev. **D83** (2011) 086005, 1012.1864.

[16] O. DeWolfe, S. Gubser, and C. Rosen, Phys. Rev. D **84** (2011) 126014, 1108.2029.

[17] S. Gubser, A. Nellore, S. Pufu, and F. Rocha, Phys. Rev. Lett. **101** (2008) 131601, 0804.1950; S. Gubser, S. Pufu, and F. Rocha, JHEP **0808** (2008) 085, 0806.0407.

[18] D. Kharzeev and K. Tuchin, JHEP **0809** (2008) 093, 0705.4280; F. Karsch, D. Kharzeev, and K. Tuchin, Phys. Lett. **B663** (2008) 217, 0711.0914.

[19] H. Song and U. Heinz, Phys. Rev. **C81** (2010) 024905, 0909.1549.

[20] S. Gubser, S. Pufu, and A. Yarom, Phys. Rev. **D78** (2008) 066014, 0805.1551.

[21] S. Gubser, S. Pufu, and A. Yarom, JHEP **0911** (2009) 050, 0902.4062.

[22] S. Gubser, Phys. Rev. **D82** (2010) 085027, 1006.0006.

and in particular the shear viscosity can be dialed to any value one wants.

Gubser and Yarom showed how to handle arbitrary small perturbations of Gubser's $SO(3)$-invariant fluid flow.[23] The main trick is to conformally map flat Minkowski space to three-dimensional de Sitter space times a line. This map translates a boost-invariant, expanding plasma of finite transverse extent into a static thermal fluid in de Sitter space. The conformal mapping facilitates a stability analysis which shows that all hydrodynamic instabilities of the $SO(3)$-invariant flow occur at such early times that the hydrodynamic expansion itself breaks down.

Also, Gubser found a way to use the $SO(3)$ subgroup of the conformal group to generate a class of solutions to the leading-order Balitsky-Kovchegov (BK) equation which again have finite transverse extent.[24] This is novel, in that most studies of the BK equation rely on replacing colliding hadrons with infinite sheets of hadronic matter.

Gubser extended these studies to complex deformations of the beamline boost symmetry. The modification is peculiar in that boost symmetry is altered by an imaginary translation in the beamline direction. The symmetry is non-unitary because the translation is not in a real direction. In published work to date,[25] this complexified symmetry principle was applied to inviscid hydrodynamics, with the result that a Bjorken-like region at mid-rapidity is bracketed by glasma-like regions at strongly forward rapidities.

## 11.6 Work of T. Dumitrescu

T. Dumitrescu's work has focused on formal aspects of supersymmetry, especially superspace constructions and constraints on supersymmetry breaking. With G. Festuccia and N. Seiberg, he provided a comprehensive analysis of the conditions implied by rigid supersymmetry for Riemannian manifolds.[26] This work focuses particularly on curved geometries involving hyperbolic three manifolds. With C. Closset, G. Festuccia, and Z. Komargodski, he developed an analysis of supersymmetric field theories on three-manifolds,[27] which feeds into the program of extracting exact information about theories with extended supersymmetry using localization. A key idea in these works is the use of background supergravity to construct theories with rigid supersymmetry. Other work by Dumitrescu and collaborators in the same period has explored the role of Chern-Simons interactions and contact terms in three-dimensional field theories with extended supersymmetry. Overall, Dumitrescu's work fits into the larger program of improving our non-perturbative understanding of interacting quantum field theories, particularly those with conformal symmetry and/or extended supersymmetry.

[23] S. Gubser and A. Yarom, Nucl. Phys. **B846** (2011) 469, 1012.1314.

[24] S. Gubser, Phys. Rev. D **84** (2011) 085024, 1102.4040.

[25] *Complex deformations of Bjorken flow,* arXiv:1210.4181 [hep-th] (2012).

[26] T. Dumitrescu, G. Festuccia, and N. Seiberg, *Exploring Curved Superspace*, JHEP 1208, 141 (2012).

[27] C. Closset, T. Dumitrescu, G. Festuccia, and Z. Komargodski, *Supersymmetric Field Theories on Three-Manifolds,* arXiv:1212.3388.

## References


[1] S. S. Gubser, "TASI lectures: Collisions in anti-de Sitter space, conformal symmetry, and holographic superconductors," arXiv:1012.5312.

[2] S. S. Gubser, "Symmetry constraints on generalizations of Bjorken flow," *Phys.Rev.* **D82** (2010) 085027, [arXiv:1006.0006].

[3] S. S. Gubser, F. D. Rocha, and A. Yarom, "Fermion correlators in non-abelian holographic superconductors," *JHEP* **1011** (2010) 085, [arXiv:1002.4416].

[4] S. S. Gubser, "Superluminal neutrinos and extra dimensions: Constraints from the null energy condition," *Phys.Lett.* **B705** (2011) 279–281, [arXiv:1109.5687].

[5] O. DeWolfe, S. S. Gubser, and C. Rosen, "Dynamic critical phenomena at a holographic critical point," *Phys.Rev.* **D84** (2011) 126014, [arXiv:1108.2029].

[6] R. Belliard, S. S. Gubser, and A. Yarom, "Absence of a Fermi surface in classical minimal four-dimensional gauged supergravity," *JHEP* **1110** (2011) 055, [arXiv:1106.6030].

[7] S. S. Gubser, "The gauge-string duality and heavy ion collisions," arXiv:1103.3636.

[8] S. S. Gubser, "Conformal symmetry and the Balitsky-Kovchegov equation," *Phys.Rev.* **D84** (2011) 085024, [arXiv:1102.4040].

[9] O. DeWolfe, S. S. Gubser, and C. Rosen, "A holographic critical point," *Phys.Rev.* **D83** (2011) 086005, [arXiv:1012.1864].

[10] S. S. Gubser and A. Yarom, "Conformal hydrodynamics in Minkowski and de Sitter spacetimes," *Nucl.Phys.* **B846** (2011) 469–511, [arXiv:1012.1314].

[11] O. DeWolfe, S. S. Gubser, and C. Rosen, "Fermi surfaces in N=4 Super-Yang-Mills theory," *Phys.Rev.* **D86** (2012) 106002, [arXiv:1207.3352].

[12] S. S. Gubser and J. Ren, "Analytic fermionic Green's functions from holography," *Phys.Rev.* **D86** (2012) 046004, [arXiv:1204.6315].

[13] H. Bantilan, F. Pretorius, and S. S. Gubser, "Simulation of Asymptotically AdS5 Spacetimes with a Generalized Harmonic Evolution Scheme," *Phys.Rev.* **D85** (2012) 084038, [arXiv:1201.2132].

[14] O. DeWolfe, S. S. Gubser, and C. Rosen, "Fermi Surfaces in Maximal Gauged Supergravity," *Phys.Rev.Lett.* **108** (2012) 251601, [arXiv:1112.3036].

[15] J. Ren, "One-dimensional holographic superconductor from $AdS_3/CFT_2$ correspondence," *JHEP* **1011** (2010) 055, [arXiv:1008.3904].

[16] J. Ren, "Analytic quantum critical points from holography," arXiv:1210.2722.

[17] C. Albertus, Y. Aoki, P. Boyle, N. Christ, T. Dumitrescu, *et. al.*, "Neutral B-meson mixing from unquenched lattice QCD with domain-wall light quarks and static b-quarks," *Phys.Rev.* **D82** (2010) 014505, [arXiv:1001.2023].

[18] T. T. Dumitrescu, Z. Komargodski, and M. Sudano, "Global Symmetries and D-Terms in Supersymmetric Field Theories," *JHEP* **1011** (2010) 052, [arXiv:1007.5352].

[19] T. T. Dumitrescu, Z. Komargodski, N. Seiberg, and D. Shih, "General Messenger Gauge Mediation," *JHEP* **1005** (2010) 096, [arXiv:1003.2661].

[20] F. Dumitrescu, "On 2-dimensional topological field theories," arXiv:1008.4920.

[21] T. T. Dumitrescu and N. Seiberg, "Supercurrents and Brane Currents in Diverse Dimensions," *JHEP* **1107** (2011) 095, [arXiv:1106.0031].

[22] T. T. Dumitrescu and Z. Komargodski, "Aspects of supersymmetry and its breaking," *Nucl.Phys.Proc.Suppl.* **216** (2011) 44–68.

[23] C. Closset, T. T. Dumitrescu, G. Festuccia, and Z. Komargodski, "Supersymmetric Field Theories on Three-Manifolds," arXiv:1212.3388.

[24] C. Closset, T. T. Dumitrescu, G. Festuccia, Z. Komargodski, and N. Seiberg, "Contact Terms, Unitarity, and F-Maximization in Three-Dimensional Superconformal Theories," *JHEP* **1210** (2012) 053, [arXiv:1205.4142].

[25] C. Closset, T. T. Dumitrescu, G. Festuccia, Z. Komargodski, and N. Seiberg, "Comments on Chern-Simons Contact Terms in Three Dimensions," *JHEP* **1209** (2012) 091, [arXiv:1206.5218].

[26] T. T. Dumitrescu, G. Festuccia, and N. Seiberg, "Exploring Curved Superspace," *JHEP* **1208** (2012) 141, [arXiv:1205.1115].

[27] T. T. Dumitrescu and G. Festuccia, "Exploring Curved Superspace (II)," *JHEP* **1301** (2013) 072, [arXiv:1209.5408].

# 12 Theoretical Cosmology

**Personnel:** P. Steinhardt; (Postdoctoral Fellows) R. Caldwell, T. Battefeld, E. Pajer, A. Tolley, (Graduate Students) L. Boyle, D. Baumann, A. Dahlen, J. Erickson, G. Huey, J. Khoury, K. Mack, A. Upadhye, D. Wesley, B. Xue, I Zlatev

## 12.1 Introduction

Steinhardt's research group in theoretical cosmology has made numerous major contributions during the course of this contract to: (1) the inflationary model of the universe; (2) the development of an alternatives, the ekpyrotic and cyclic models of the universe; (3) the dark energy problem; (4) the dark matter problem; and (5) the baryon asymmetry problem. In addition, support during this period enabled Steinhardt to seed projects in condensed matter physics and geophysics that have spun off substantial research efforts that now receive independent support from the NSF, the Princeton University innovation funds, and private investors. The subsections below elaborate briefly on the highlights of the cosmology contributions listed above.

### 12.1.1 Inflationary Models of the universe

Progress on inflationary theory has included new insights on string inflation and a reconsideration of inflationary predictions for scalar and tensor fluctuations.

With grad students Daniel Baumann and Anatoly Dymarsky, post-doc McAllister, and Professr Igor Klebanov, Steinhardt examined D-brane inflation [1], based on a warped conifold that includes holomorphically-embedded D7-branes involved in moduli stabilization. They showed that the presence of the D7-branes significantly modifies the inflaton potential. They constructed an example based on a very simple and symmetric embedding due to Kuperstein in which it is possible to fine-tune the potential so that slow roll inflation can occur. However, the resulting model is extremely delicate: inflation only occurs in the vicinity of an inflection point, and the cosmological predictions are extremely sensitive to the precise shape of the potential. Hence, one of the most promising approaches to inflationary cosmology is in jeopardy.

Graduate student Latham Boyle and Steinhardt studied the full gravitational wave spectrum generated by inflationary models, ranging from the Hubble scale down to the length scales accessible by space-based laser-interferometer gravitational wave detectors.[2] They demonstrated that a gravitational wave with wavenumber $k$ preserves information about the physical conditions when it was generated and also when it re-entered the horizon after inflation. Hence, by combining measurements on the cosmic microwave background scales and at scales probed by space-based detectors, the gravitational wave spectrum can provide a unique probe of the universe at temperatures near the electroweak and QCD scales.

Boyle, Steinhardt and Turok[3] have also reconsidered the predictions of inflation for the spectral index of scalar (energy density) fluctuations $n_s$ and the tensor/scalar ratio $(r)$r. They constructed a new discrete, model-independent measure of the degree of fine-tuning required to obtain a given combination of ($n_s$, $r$). Using this measure, they found that, except for cases with numerous unnecessary degrees of fine-tuning, $n_s$ is about 0.97 and $r > 10^{-2}$, a range that should be detectable in proposed cosmic microwave background anisotropy and polarization experiments and direct gravitational wave searches, adding motivation for the study by Boyle and Steinhardt above. The announcement by the WMAP and Planck teams reported value of $n_s$ and $r$ that are consistent thus far with the inflationary prediction found by Boyle *et al.*

Boyle and Steinhardt [4] developed a sequence of observational "bootstrap" tests that can potentially prove inflation. The conventional view had been that this is not possible because there is too much freedom in constructing inflationary models. For the bootstrap tests, though, one uses measurements of the density and gravitational wave spectrum to separately determine the number of e-folds of inflation that occurred after a given mode left the horizon during inflation and the number of e-folds of decelerated expansion that occurred since. The bootstrap test is a sequence of measurements that progressively checks whether the two are equal.

## 12.2 Cyclic Models of the universe

Steinhardt and Neil Turok introduced the the 'cyclic model' of the universe [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 30, 31], a radical alternative to the standard big bang/inflationary model, an elaboration of an earlier proposal known as the 'ekpyrotic universe' [32, 33, 34, 35, 36, 37, 38] The defining features of the cyclic model are: (a) the big bang is a transition to an earlier phase of evolution, rather than the beginning of space-time; (b) the universe undergoes a periodic sequence of big bangs and big crunches going backward (or forward) in time; and (c) the key events that shape the large-scale structure of the universe – the large-scale homogeneity, isotropy, flatness and density fluctuations – occur during "ekpyrotic" phase preceding the last bang, rather than a period of rapid inflation after the bang. The ekpyrotic phase is defined as a period of contraction with an equation of state $w \gg 1$, whether in the context of 5d colliding branes or 4d quantum field theory. Despite these dramatic differences, it is possible to recover all of the successful predictions of the standard model and to have novel solutions to the cosmological constant and baryon asymmetry problems. Furthermore, it has revealed at least two observational tests that will make it possible to distinguish the inflationary and cyclic scenarios.

The cyclic model was originally motivated by M-theory, in which our universe comprises a membrane or "brane" in a higher dimensional space at the boundary of an extra dimension. A second brane lies at the other boundary, and there may be additional bulk branes. The cycles of expansion and collision correspond to the collision and bouncing apart of the outermost branes. The apparent contraction of the universe is actually the contraction of the extra dimension(s). Hence, the density of matter and radiation on the branes remains finite when they collide. Fluctuations are created when quantum effects produce ripples in the branes as they approach, which, by means discussed below, ultimately result in time delays between when different regions collide and reheat. The remarkable result is that, at least in principle (see below), the spectrum of density perturbations can be nearly scale-invariant even though the physical process involved is completely different from inflation.

Paul McFadden, Neil Turok and Steinhardt studied cosmological perturbations in a five-dimensional background consisting of two separating or colliding boundary (orbifold) branes, as a function of the their relative speed $v$ compared to the speed of light $c$ [16]. The study showed the precise relation 4D and 5D density perturbation theory, proving that they agree to leading order but differ at order $(v/c)^2$. At this order, one must consider the effect of bulk excitations which result a non-trivial mixing of the scalar field fluctuations (a growing time-delay mode) with the decaying (curvature) mode.

Consideration of the 5d example led to the realization that curvature perturbations can be generated in a contracting phase in an ordinary 4d quantum field theory, without reference to extra dimensions or branes [23, 24, 27]. The key is to have two or more scalar fields that obtain scale-invariant fluctuations during the ekpyrotic phase (analogous to the radion and bulk modes in the 5d theory) in which case a linear combination of decaying curvature fluctuations and growing entropic fluctuations are generated, both of which are scale-invariant. This process for generating curvature perturbations, referred to as the "entropic mechanism."

An important byproduct of the entropic mechanism is the generation of non-gaussian fluctuations at a level that is ten times (or more) larger than simple inflationary models predict, providing a new experimental signature for distinguish ekpyrotic/cyclic and inflationary scenarios [23, 24, 27]. The non-gaussianity can be observed in the three-point temperature correlation of the cosmic microwave background or mass density, especially the correlations between the vertices of squeezed triangles with two long sides and one short one. The strength of the non-gaussianity is parameterized by the constant $f_{NL}$, which is $\mathcal{O}(1)$ or less for inflationary models with a single scalar field and canonical kinetic energy, but $\mathcal{O}(10)$ in the cyclic model, for example. Lehners and Steinhardt recently showed that the predictions agree well with WMAP+SPT and Planck2013 data [31].

Steinhardt and collaborators also investigated the growth of perturbations in the cyclic model over the course of many cycles [18]. The key question they addressed is whether the perturbations and structure generated in one cycle disrupt or otherwise scar subsequent cycles. They showed that this does not occur. Instead, they showed that fluctuations from earlier cycles are stretched to superhorizon scales that have no effect on subhorizon observations. Along the way, the analysis resolved a number of paradoxes in the generation of density perturbations and exposed the fact that the superhorizon structure of the universe cannot be described as a simple Friedmann Robertson Walker universe because different sectors are out of phase in their cycling with respect to one another

## 12.3 Dark Energy

Evidence from Type Ia supernova that the expansion of the universe is accelerating led Steinhardt and collaborators to explore the possibility that the universe is dominated by a form of dark energy with negative pressure, which they dubbed "quintessence" [39, 40, 41, 42]. Quintessence is a proposed explanation of the accelerated expansion that is a viable alternative to a static, uniform vacuum energy or cosmological constant: Steinhardt and collaborators studied how quintessence can assume different equations-of-state [39], can have a different effect on the expansion of the universe and on the evolution of large-scale structure [43, 44], can modify the gravitational wave spectrum from inflation [45], and can produce a different imprint on the cosmic microwave background [46].

A key problem with quintessence or vacuum energy is explaining why the energy density should be comparable to the matter energy density today. Zlatev, Wang and Steinhardt have discovered a mechanism, called “tracker fields,” which avoids the coincidence problem [47, 44]. Tracker fields are a form of quintessence which have an equation-of-motion with attractor-like solutions in which initial conditions rapidly converge to a common, cosmic evolutionary track ultimately leading to the accelerated expansion of the universe. Tracking as a means of solving the problems of initial conditions may have more general application. Future research will explore the possibility of a unified “dark sector” which explains simultaneously the quintessence-to-baryon and cold dark matter ratios, and possible relationships to light fields in superstring theory.

With I. Maor and R. Brustein, Steinhardt examined limitations on using luminosity distance to determine the equation-of-state of the universe [48]. With C. Armendariz-Picon and V. Mukhanov (Munich), Steinhardt explored $k$-essence, a model for dark energy that may address both the fine-tuning and coincidence problem associated with the other quintessence or cosmological constant explanations [49, 50]. The model consists of a non-linearly coupled scalar field with attractor dynamics causes the quintessence field to track the radiation during the radiation epoch, but to transform into a negative pressure state at the onset of matter-domination.

D. Wesley and Steinhardt [51, 52] showed how accelerated expansion, whether due to inflation or dark energy, imposes strong constraints on fundamental theories obtained by compactification from higher dimensions. For theories that obey the null energy condition (NEC), they showed that inflationary cosmology is impossible for a wide range of compactifications; and a dark energy phase consistent with observations is only possible if both Newton’s gravitational constant and the dark energy equation-of-state vary with time. If the theory violates the NEC, inflation and dark energy are only possible if the NEC-violating elements are inhomogeneously distributed in the compact dimensions and vary with time in precise synchrony with the matter and energy density in the non-compact dimensions.

They then explored how current and future measurements of $w$ (the equation of state of dark energy) and the time-variation of Newton’s constant $\dot{G}$ can be used to place tight limits on large classes of these theories (including some of the most well-motivated examples) independent of the size of the extra dimensions. As an example, they showed that models with conformally Ricci-flat metrics obeying the null energy condition (a common ansatz for Kaluza-Klein and string constructions) are highly constrained by current data and may be ruled out entirely by future dark energy and pulsar observations. The results are significant targets for WFIRST, LSST and other future dark energy experiments. Future work will develop further, stronger theorems and constraints on theories with extra dimensions.

### 12.4 Dark Matter

Steinhardt and Spergel [53] proposed that dark matter is strongly self-interacting with a cross-section and mass similar to a neutron. They argued that the favored candidates for dark matter – weakly interacting massive particles (WIMPs), such as axions and neutralinos – produce too much small scale (subgalactic) structure compared to observations. With R. Davé and B. Wandelt, they performed large simulations of the self-interacting and weakly interacting scenarios [54, 55]. Their comparisons verified that the self-interacting model resolves many of the contradictions between theory and observation found for WIMPs. With A. Kusenko, Steinhardt suggested Q-balls as a specific candidate for the self-interacting dark matter [56]. Q-balls are non-topological solitons consisting of droplets of hypercharge which can naturally satisfy the large cross-section requirements. Q-balls can also have substantial and detectable cross-sections with ordinary matter, further motivating future searches. With Adrienne Erickcek (Caltech), Dan McCammon (Wisconsin), and P.C. McGuire (McDonnell), Steinhardt derived new constraints on the the interactions between dark matter and baryonic matter based on McCammon's X-Ray Quantum Calorimeter Experiment [57]. Graduate student Katherine Mack and Steinhardt [58] derived sharp constraints based on the dark matter density on string theory models with multiple axion-like fields, as might be expected versions that include a QCD axion.

### 12.5 Baryon Asymmetry

With H. Davoudiasl, G. Kribs, R. Kitano and H. Murayama, Steinhardt proposed a new mechanism for 'gravitational baryogenesis' based on the derivative coupling between the baryonic current and the Ricci scalar [59] This kind of interaction is naturally generated by quantum corrections to gravity and becomes significant if the scalar curvature changes significantly with time. The authors show that this "gravitational baryogenesis" can occur for reasonable parameters in the early universe at a level sufficient to explain the observed baryon asymmetry.

With D. Baumann and Neil Turok, Steinhardt studied the consequences of black hole formation in the very early universe, either during reheating after inflation or after the brane collision in the cyclic model [60]. They showed that the black holes produced during this epoch come to dominate the universe decay before nucleosynthesis, and that the black holes have a density and mass distribution that would enable them to play several critical roles in cosmic evolution. Namely, during their decay, the black holes could reheat the universe and generated the observed baryon asymmetry. Furthermore, if they decay to Planck mass remnants, the remnants could account for the observed dark matter in the universe.

## References


[1] Daniel Baumann, Anatoly Dymarsky, Igor R. Klebanov, Liam McAllister, and Paul J. Steinhardt. A Delicate universe. *Phys.Rev.Lett.*, 99:141601, 2007.

[2] Latham A. Boyle and Paul J. Steinhardt. Probing the early universe with inflationary gravitational waves. *Phys.Rev.*, D77:063504, 2008.

[3] Latham A. Boyle, Paul J. Steinhardt, and Neil Turok. Inflationary predictions reconsidered. *Phys.Rev.Lett.*, 96:111301, 2006.

[4] Latham Boyle and Paul J. Steinhardt. Testing Inflation: A Bootstrap Approach. *Phys.Rev.Lett.*, 105:241301, 2010.

[5] P.J. Steinhardt and N. Turok. A cyclic model of the universe. *Science*, 296:1436–1439, 2002.

[6] Paul J. Steinhardt and Neil Turok. Cosmic evolution in a cyclic universe. *Phys.Rev.*, D65:126003, 2002.

[7] Paul J. Steinhardt and Neil Turok. The Cyclic universe: An Informal introduction. *Nucl.Phys.Proc.Suppl.*, 124:38–49, 2003.

[8] Paul J. Steinhardt and Neil Turok. Is vacuum decay significant in ekpyrotic and cyclic models? *Phys.Rev.*, D66:101302, 2002.

[9] Steven Gratton, Justin Khoury, Paul J. Steinhardt, and Neil Turok. Conditions for generating scale-invariant density perturbations. *Phys.Rev.*, D69:103505, 2004.

[10] Justin Khoury, Paul J. Steinhardt, and Neil Turok. Inflation versus cyclic predictions for spectral tilt. *Phys.Rev.Lett.*, 91:161301, 2003.

[11] Andrew J. Tolley, Neil Turok, and Paul J. Steinhardt. Cosmological perturbations in a big crunch / big bang space-time. *Phys.Rev.*, D69:106005, 2004.

[12] Justin Khoury, Paul J. Steinhardt, and Neil Turok. Designing cyclic universe models. *Phys.Rev.Lett.*, 92:031302, 2004.

[13] Latham A. Boyle, Paul J. Steinhardt, and Neil Turok. The Cosmic gravitational wave background in a cyclic universe. *Phys.Rev.*, D69:127302, 2004.

[14] Paul J. Steinhardt and Neil Turok. The Cyclic model simplified. *New Astron.Rev.*, 49:43–57, 2005.

[15] Neil Turok, Malcolm Perry, and Paul J. Steinhardt. M theory model of a big crunch / big bang transition. *Phys.Rev.*, D70:106004, 2004.

[16] Paul L. McFadden, Neil Turok, and Paul J. Steinhardt. Solution of a braneworld big crunch / big bang cosmology. *Phys.Rev.*, D76:104038, 2007.

[17] Paul J. Steinhardt and Neil Turok. Why the cosmological constant is small and positive. *Science*, 312:1180–1182, 2006.

[18] Joel K. Erickson, Steven Gratton, Paul J. Steinhardt, and Neil Turok. Cosmic perturbations through the cyclic ages. *Phys.Rev.*, D75:123507, 2007.

[19] Jean-Luc Lehners, Paul McFadden, Neil Turok, and Paul J. Steinhardt. Generating ekpyrotic curvature perturbations before the big bang. *Phys.Rev.*, D76:103501, 2007.

[20] Jean-Luc Lehners and Paul J. Steinhardt. Non-Gaussian density fluctuations from entropically generated curvature perturbations in Ekpyrotic models. *Phys.Rev.*, D77:063533, 2008.

[21] Jean-Luc Lehners and Paul J. Steinhardt. Intuitive understanding of non-gaussianity in ekpyrotic and cyclic models. *Phys.Rev.*, D78:023506, 2008.

[22] David Garfinkle, Woei Chet Lim, Frans Pretorius, and Paul J. Steinhardt. Evolution to a smooth universe in an ekpyrotic contracting phase with $w > 1$. *Phys.Rev.*, D78:083537, 2008.

[23] Jean-Luc Lehners, Paul J. Steinhardt, and Neil Turok. The Return of the Phoenix Universe. *Int.J.Mod.Phys.*, D18:2231–2235, 2009.

[24] Jean-Luc Lehners and Paul J. Steinhardt. Non-Gaussianity Generated by the Entropic Mechanism in Bouncing Cosmologies Made Simple. *Phys.Rev.*, D80:103520, 2009.

[25] Justin Khoury and Paul J. Steinhardt. Adiabatic Ekpyrosis: Scale-Invariant Curvature Perturbations from a Single Scalar Field in a Contracting Universe. *Phys.Rev.Lett.*, 104:091301, 2010.

[26] BingKan Xue and Paul J. Steinhardt. Unstable growth of curvature perturbation in non-singular bouncing cosmologies. *Phys.Rev.Lett.*, 105:261301, 2010.

[27] Jean-Luc Lehners and Paul J. Steinhardt. Dynamical Selection of the Primordial Density Fluctuation Amplitude. *Phys.Rev.Lett.*, 106:081301, 2011.

[28] BingKan Xue and Paul J. Steinhardt. Evolution of curvature and anisotropy near a nonsingular bounce. *Phys.Rev.*, D84:083520, 2011.

[29] Itzhak Bars, Shih-Hung Chen, Paul J. Steinhardt, and Neil Turok. Antigravity and the Big Crunch/Big Bang Transition. *Phys.Lett.*, B715:278–281, 2012.

[30] Itzhak Bars, Shih-Hung Chen, Paul J. Steinhardt, and Neil Turok. Complete Set of Homogeneous Isotropic Analytic Solutions in Scalar-Tensor Cosmology with Radiation and Curvature. *Phys.Rev.*, D86:083542, 2012.

[31] Jean-Luc Lehners and Paul J. Steinhardt. Planck 2013 results support the simplest cyclic models. 2013.

[32] Justin Khoury, Burt A. Ovrut, Paul J. Steinhardt, and Neil Turok. The Ekpyrotic universe: Colliding branes and the origin of the hot big bang. *Phys.Rev.*, D64:123522, 2001.

[33] Justin Khoury, Burt A. Ovrut, Paul J. Steinhardt, and Neil Turok. A Brief comment on 'The Pyrotechnic universe'. 2001.

[34] Justin Khoury, Burt A. Ovrut, Nathan Seiberg, Paul J. Steinhardt, and Neil Turok. From big crunch to big bang. *Phys.Rev.*, D65:086007, 2002.

[35] Justin Khoury, Burt A. Ovrut, Paul J. Steinhardt, and Neil Turok. Density perturbations in the ekpyrotic scenario. *Phys.Rev.*, D66:046005, 2002.

[36] Joel K. Erickson, Daniel H. Wesley, Paul J. Steinhardt, and Neil Turok. Kasner and mixmaster behavior in universes with equation of state $w > 1$. *Phys.Rev.*, D69:063514, 2004.

[37] Latham A. Boyle, Paul J. Steinhardt, and Neil Turok. A New duality relating density perturbations in expanding and contracting Friedmann cosmologies. *Phys.Rev.*, D70:023504, 2004.

[38] Justin Khoury and Paul J. Steinhardt. Generating Scale-Invariant Perturbations from Rapidly-Evolving Equation of State. *Phys.Rev.*, D83:123502, 2011.

[39] R.R. Caldwell, Rahul Dave, and P.J. Steinhardt. Quintessential cosmology: Novel models of cosmological structure formation. *Astrophys.Space Sci.*, 261:303–310, 1998.

[40] P.J. Steinhardt. A quintessential introduction to dark energy. *Phil.Trans.Roy.Soc.Lond.*, A361:2497–2513, 2003.

[41] Amol Upadhye, Mustapha Ishak, and Paul J. Steinhardt. Dynamical dark energy: Current constraints and forecasts. *Phys.Rev.*, D72:063501, 2005.

[42] P.J. Steinhardt. Quintessential ideas. *Phys.Scripta*, T117:34–39, 2005.

[43] Li-Min Wang and Paul J. Steinhardt. Cluster abundance constraints on quintessence models. *Astrophys.J.*, 508:483–490, 1998.

[44] Li-Min Wang, R.R. Caldwell, J.P. Ostriker, and Paul J. Steinhardt. Cosmic concordance and quintessence. *Astrophys.J.*, 530:17–35, 2000.

[45] R.R. Caldwell and Paul J. Steinhardt. The Imprint of gravitational waves in models dominated by a dynamical cosmic scalar field. *Phys.Rev.*, D57:6057–6064, 1998.

[46] Greg Huey, Li-Min Wang, Rahul Dave, R.R. Caldwell, and Paul J. Steinhardt. Resolving the cosmological missing energy problem. *Phys.Rev.*, D59:063005, 1999.

[47] Ivaylo Zlatev, Li-Min Wang, and Paul J. Steinhardt. Quintessence, cosmic coincidence, and the cosmological constant. *Phys.Rev.Lett.*, 82:896–899, 1999.

[48] Irit Maor, Ram Brustein, and Paul J. Steinhardt. Limitations in using luminosity distance to determine the equation of state of the universe. *Phys.Rev.Lett.*, 86:6, 2001.

[49] C. Armendariz-Picon, Viatcheslav F. Mukhanov, and Paul J. Steinhardt. A Dynamical solution to the problem of a small cosmological constant and late time cosmic acceleration. *Phys.Rev.Lett.*, 85:4438–4441, 2000.

[50] C. Armendariz-Picon, Viatcheslav F. Mukhanov, and Paul J. Steinhardt. Essentials of k essence. *Phys.Rev.*, D63:103510, 2001.

[51] Paul J. Steinhardt and Daniel Wesley. Dark Energy, Inflation and Extra Dimensions. *Phys.Rev.*, D79:104026, 2009.

[52] Paul J. Steinhardt and Daniel Wesley. Exploring extra dimensions through observational tests of dark energy and varying Newton's constant. 2010.

[53] David N. Spergel and Paul J. Steinhardt. Observational evidence for selfinteracting cold dark matter. *Phys.Rev.Lett.*, 84:3760–3763, 2000.

[54] Romeel Dave, David N. Spergel, Paul J. Steinhardt, and Benjamin D. Wandelt. Halo properties in cosmological simulations of selfinteracting cold dark matter. *Astrophys.J.*, 547:574–589, 2001.

[55] Benjamin D. Wandelt, Romeel Dave, Glennys R. Farrar, Patrick C. McGuire, David N. Spergel, et al. Selfinteracting dark matter. pages 263–274, 2000.

[56] Alexander Kusenko and Paul J. Steinhardt. Q ball candidates for selfinteracting dark matter. *Phys.Rev.Lett.*, 87:141301, 2001.

[57] Adrienne L. Erickcek, Paul J. Steinhardt, Dan McCammon, and Patrick C. McGuire. Constraints on the Interactions between Dark Matter and Baryons from the X-ray Quantum Calorimetry Experiment. *Phys.Rev.*, D76:042007, 2007.

[58] Katherine J. Mack and Paul J. Steinhardt. Cosmological Problems with Multiple Axion-like Fields. *JCAP*, 1105:001, 2011.

[59] Hooman Davoudiasl, Ryuichiro Kitano, Graham D. Kribs, Hitoshi Murayama, and Paul J. Steinhardt. Gravitational baryogenesis. *Phys.Rev.Lett.*, 93:201301, 2004.

[60] Daniel Baumann, Paul J. Steinhardt, and Neil Turok. Primordial Black Hole Baryogenesis. 2007.