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Improving our theoretical understanding of high energy collider experiment

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Overview of accomplishments

Over the past few years, Prof. Sullivan has worked at the interface of theory and experiment to reveal the subtle interactions between our theories about natural processes and their experimental realizations. The research conducted looks forward, and provides students and postdoctoral scholars the opportunity to join with Prof. Sullivan in resolving the challenges that dominated high energy physics then and over the coming decade. The theory task has produced nine papers [1–9], six of which have appeared in refereed journals. Details regarding these projects, including a Standard Model explanation of the CDF dijet excess, proposals for how to find and determine the properties of a Higgs-like boson, investigations of the Tevatron forward-backward asymmetry at the LHC, and more are summarised below.

The basis of this project is the realization that the limiting factor in experimental measurements is often a reliance on an unstated theoretical assumption; principally, that what is observed in a detector is defined in the same manner as what is predicted by theory. A few years ago, Sullivan determined this was not the case in the presence of additional QCD radiation in single-top-quark production, the flagship measurement of the Tevatron. This observation led to one of the early jet matching schemes [10], which was used by the CDF and DØ Collaborations in their discovery of single-top-quark production [11], and continues to be used as an effective precision phenomenological tool [12].

Dr. Arjun Menon (postdoc) continued earlier work under the grant, participating in two projects with Dr. Sullivan, and two independent projects. Dr. Menon left for the University of Oregon after August 2011. Dr. Hao Zhang (postdoc) began in October 2011, and was supported his first five months by this grant, and the rest by a separate grant from Argonne National Laboratory. Daniel Duffty (graduate student) has participated in work under this grant, and presented his first research talk at a conference.

During the 2009-2011 academic years, Prof. Sullivan worked with Yaofu Zhou (undergraduate), Daniel Duffty (graduate student), and Dr. Arjun Menon (advanced research associate) to address three independent areas of research important to the Fermilab Tevatron and CERN LHC experiments. This work has attracted national as well as international attention, resulting in numerous publications, conference presentations, and invitations to serve as a convener at major conferences. Prof. Sullivan also strengthened ties between the theory groups at ANL, FNAL and IIT.

More recently, Prof. Sullivan collaborated with Edmond L. Berger to show that backgrounds to Higgs dilepton and supersymmetric trilepton signatures, the most important searches at the Tevatron and LHC, were significantly larger than expected [13, 14]. These analyses merged the theoretical underpinnings of isolated lepton production, an understanding of showering event generators, and details of experimental reconstruction to demonstrate why the decay of bottom and charm hadrons into isolated leptons had escaped previous experimental observation. Evidence of these isolated leptons from b decays has recently been observed in the CDF detector at Fermilab [15] based on our predictions [16].

In April 2011, the CDF Collaboration made headlines when they announced the potential discovery of a new unexpected resonance in their Wjj data sample [17]. Within two weeks, my postdoc Arjun Menon andProf. Sullivan demonstrated in a Physics Review D Rapid Communications [18], that the peak observed by CDF was consistent with a background of single-top-quark production as seen by the CDF measurement of that channel. We further predicted the DØ Collaboration would see a very small excess in Wjj, consistent with their measurement of single-top-quark production. By August 2011, we released an update [19] that confirmed both the explanation of the CDF anomaly, and the prediction of a subsequent null result from DØ [20]. This research has pointed to a need for the CDF and DØ Collaborations to re-examine b-jet tagging in their low multiplicity states.

The quest to understand the electroweak symmetry breaking (EWSB) mechanism has been emboldened by the search for a Higgs boson. Direct searches at the CERN LEP collider established a lower limit on the mass of a Standard Model (SM) Higgs boson of $m_H > 114.4$ GeV [21]. Indirect constraints using the latest measurements of the top-quark mass, W boson mass, and electroweak precision fits predict $m_H < 163$ GeV [22]. The Minimal Supersymmetric Standard Model (MSSM) predicts a lightest Higgs boson mass less than 140 GeV [23]. Current searches from the Tevatron and LHC have excluded a Standard Model-like Higgs near 170 GeV [24–26], and are putting pressure on lower masses. If a Higgs-like boson is found, the consistency of the EWSB mechanism will be confirmed by comparing the relations between precision measurements of the Higgs, top quark, and W boson masses.

Recently, Arjun Menon and Prof. Sullivan developed the first new method in over a decade to search for a Standard Model-like Higgs boson. In two papers we propose looking for a Higgs mass peak in the final state of a two or three jets, a lepton, and missing energy, where one jet is charm tagged. This analysis has the potential to be the second most powerful channel in both the Tevatron exclusion analyses, and the LHC discovery searches. Unlike current dilepton searches, which measure a transverse mass, this new analysis channel can reconstruct the Higgs mass, and has a cleaner signal to background ratio. In addition, these papers develop a strong motivation for generic improvement of charm tagging algorithms at the hadron colliders, as the significance grows linearly with charm acceptance rates. Groups at the Tevatron and LHC are currently investigating how to fold this new channel into their combined analyses.

In collaboration with an undergraduate, Yaofu Zhou, we have produced a computer code that allows for the complete theoretical modeling of arbitrary charged vector or axial vector currents, generally called W' bosons. This code integrates with the standard analysis package MadEvent, and will be publicly distributed this winter. In the production of this code, we discovered that generic searches performed for W' bosons must be reinterpreted for a class of theories whose Lagrangians have a different structure than previously considered. This work will be submitted to the Journal of High Energy Physics.

Interdisciplinary and educational impact

We are in an age of discovery in high energy physics. The search for new and varied forms of matter is exciting, but we must also maximize this opportunity to deepen our understanding of the forces and matter we have already found. Success will require a coordinated effort of the theoretical, experimental, and accelerator communities, and a new generation of scientists trained to lead these efforts in the future. This project will strengthen education, support the experimental collaborations, and improve communications between scientific communities.

Experimental connections:

Prof. Sullivan has worked closely with the CDF, DØ, ATLAS, and CMS experimental collaborations to ensure that his research will have practical and immediate application. He released the ZTOP program [27] used in the discovery of single-top-quark production, and published computer codes that improved the speed of CTEQ parton distribution functions [28]. He also provided enhancements to and support for the use of MadEvent [29,30], PYTHIA [31] and MCFM [32]. These tools provided the numerical backbone and interface between high energy theory and experiment. Most of the topics in this project have grown out of experimental concerns, and this project will continue to closely engage with the collaborations to address the most pressing issues.

Theory Community Leadership:

Prof. Sullivan initiated a Joint Theory Institute between IIT and Argonne National Laboratory that hosted 68 postdocs and faculty members from around the world May 18–22, 2009. This workshop focused on identifying and beginning to address the theoretical issues associated with the new energy regime of the LHC. He broadened his physics community participation by co-organizing the "NuFact09: Neutrino Factories, Superbeams and Beta Beams" workshop hosted jointly by Fermilab and IIT July 20–25, 2009. In 2013, he will bring the 43rd (XLIII) International Symposium on Multiparticle Dynamics to IIT. ISMD 2013 will cover new and topical subjects related to multiparticle dynamics as observed in elementary particles, heavy ion collisions, and in cosmic ray showers.

CTEQ involvement:

The Coordinated Theoretical-Experimental Project on QCD (CTEQ) is a multi-institutional collaboration which pursues a broad program of research and education with a focus on QCD and its applications in high energy physics. CTEQ provides a forum for interaction between theorists and experimentalists, provides tools central to the high energy physics effort, and hosts summer schools on the techniques and applications of QCD. Prof. Sullivan contributed to the CTEQ effort in parton distribution functions [28], and taught advanced classes at the 2007, 2009 and 2011 CTEQ Summer Schools, held in Madison, Wisconsin.

Educational development:

As the scientific enterprise finds new strength in blurring the boundaries of disciplines, a need has arisen in the United States for students who have the training to understand the integration of theoretical and experimental research. Prof. Sullivan is addressing this need in several ways: as Chairman of the IIT Physics Graduate Curriculum Committee, which is successfully modernizing and growing the overall physics graduate education program at IIT, training and mentoring graduate and undergraduate students with a focus on bridging the gap between theory and experiment, and collaborating with and mentoring postdoctoral scholars as they prepare for the next stage of their careers. An investment of resources in students and postdocs by this project will be leveraged to support the needs of the field today, and to train future leaders of the field.

Daya Bay Reactor Neutrino Experiment

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Introduction

The Daya Bay Reactor Anti-Neutrino Experiment is a neutrino oscillation experiment designed to observe and measure the neutrino mixing angle θ_{13}. This is being accomplished by measuring the relative rates and energy spectra of reactor electron antineutrinos with multiple detectors positioned at different baselines. The Day Bay nuclear power complex is located in southern China about 55 km north-east from Victoria Harbor in Hong Kong and is one of the most prolific sources of antineutrinos in the world. Currently the three pairs of reactor cores (Daya Bay, Ling Ao I, and Ling Ao II, separated by about 1.1 km) generate 17.4 GW_{th} of thermal power. The Daya Bay complex is among the five most powerful reactor complexes in the world.

Civil construction was completed in the summer of 2012. All eight Antineutrino Detectors (ADs) have been assembled, filled, and deployed. Analysis of the early data set lead to the discovery earlier this year of a non-zero value for θ_{13} [33]. IIT's primary contributions involve detector assembly and filling, electronic readout, cables and grounding, DAQ, online, and computer control and monitoring; however, we have made strong contributions to offline code development. The IIT Daya Bay group consisted of Profs. Torun, Terry, and White, Dr. Qun Wu, Mr. Brandon Seilhan, Ms. Emily Draeger and Mr. Jose de Arcos (graduate students). Prof. Terry was not supported by this grant and Dr. Wu recently left IIT for a faculty position at Shondong University. Dr. Seilhan completed his PhD in August 2011 and is now employed by LLNL.

Accomplishments and Contributions

Prof. White was the US Level-2 project manager for electronics, DAQ, and online systems (WBS 1.4). In addition to technical and scientific oversight, Prof. White serves as editor for all WBS1.4 technical papers. He also serves on the Daya Bay Technical Board, was recently renewed as one of three members of the publication committee, and was elected IB Chair in January 2011. The technical board also requested that Prof. White work with Chinese engineers and scientists to oversee cabling and grounding in the experimental halls. He was also appointed by the spokespersons as co-editor for the first three collaboration physics papers, all released and published in 2012. Prof. Torun was US L3 for computer control and monitoring. Prof. Terry has been consulting with the chemists working on the LS and Gd-LS for Daya Bay. He has an extensive background in chemical and nuclear physics and has been sharing his experience and expertise with the IIT Daya Bay group members (primarily the students). As mentioned above, Prof. Terry was not funded through this grant.

IIT was the lead US institution for testing and evaluation of the readout electronics being designed and built in China. Prof. White with Dr. Wu assembled and commissioned a VME based testing system. An IIT undergraduate (Mr. Valls) also participated in these activities. US participation in electronic testing was complementary to the work in China and proved to be valuable in moving the electronic design process forward.

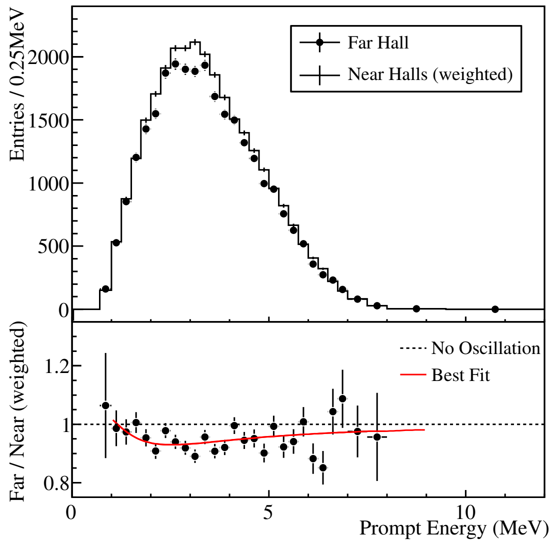

Figure 1: Top: Measured prompt energy spectrum of the far hall (sum of three ADs) compared with the no-oscillation prediction based on the measurements of the two near halls. Spectra were background subtracted. Uncertainties are statistical only. Bottom: The ratio of measured and predicted no-oscillation spectra. The solid curve is the expected ratio with oscillations, calculated as a function of neutrino energy assuming $\sin^2 2\theta_{13} = 0.089$ obtained from the rate-based analysis. The dashed line is the no-oscillation prediction.

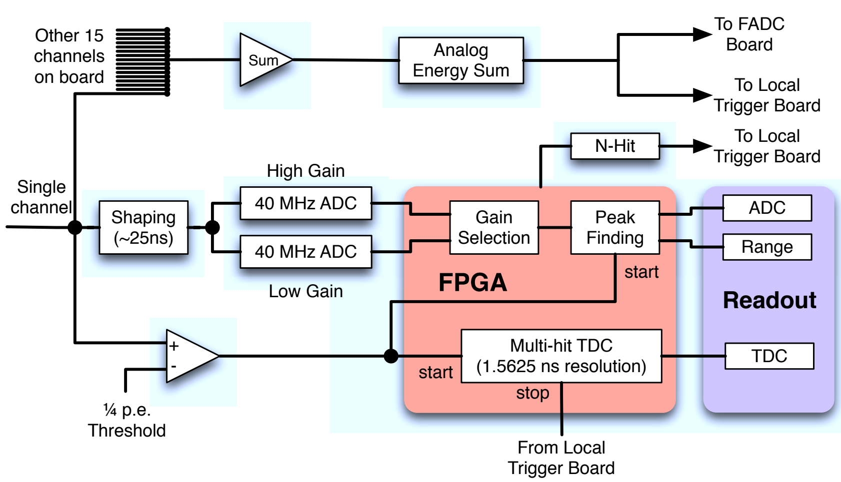

Figure 2: Schematic representation of a single PMT electronic readout channel implemented for the Daya Bay experiment.

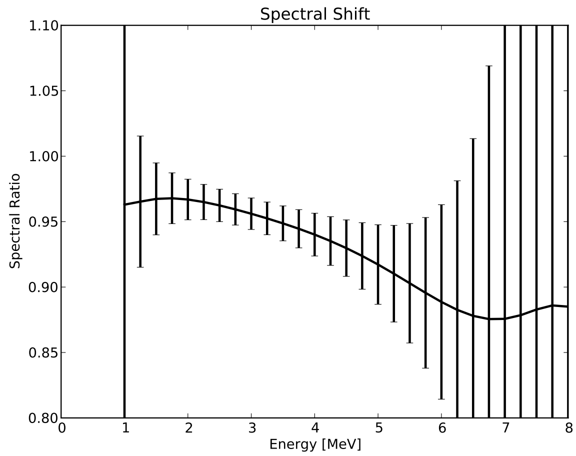

Figure 3: Dr. Seilhan developed a stand-along software package that predicts the spectral shift in observed neutrino interactions as the isotopic concentrations in the fuel-rods mature.

Dr. Seilhan completed his PhD thesis in 2011 and is currently employed as a postdoc at LLNL. While on-site, Dr. Seilhan contributed to detector construction; however, his primary contributions were software related. Dr. Seilhan helped develop the core analysis and simulation software and was a central player in the development of the electronics and trigger simulation code and emulating the eventual real data readout mechanisms and formats. He also made valuable contributions to the design of how the overall simulation chain should operate. Specific contributions include writing software within the G4dyb (legacy) software package to simulate the triggering and readout of the Antineutrino Detectors. While porting the Trigger, Readout, and Electronics simulations from G4dyb to NuWa he developed and implemented persistent forms of the data objects. In collaboration with an undergraduate student, Kevin Gullikson, Dr. Seilhan developed an event-display (the collaboration's first event display) using ROOT and openGL. In this display, the AD PMTs are color-coded based on the number of photo-electrons produced at its photo-cathode during an event. We then generalized the event display to allow coloring of the PMTs based on arbitrary variables defined at run-time by the user. The generalized event display is framework independent and is therefore compatible with both the legacy code and the NuWa frameworks.

Dr. Seilhan developed software and methodology to estimate the antineutrino flux from the reactor cores of the Daya Bay experiment. From existing literature he identified sources within a reactor core and their relative contributions and has reproduced the primary component of the anti-neutrino spectrum which comes from the four main fissile elements: ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. The relative contributions of each isotope is dependent of the amount of each in the core and the instantaneous fission rate. To properly model the anti-neutrino spectrum, the "burn-up effect" which changes the relative proportions of isotopes within a core during a fuel cycle was simulated. Dr. Seilhan attended a week long training course at Oak Ridge National Lab for the SCALE (**S**tandardized **C**omputer **A**nalysis for **L**icensing **E**valuation) software package. The course focused on the ORIGEN-ARP (**O**ak **R**idge **I**sotope **Gen**eration) and TRITON (**T**ransport **R**igor **I**mplemented with **T**ime-dependent **O**peration for **N**eutronic depletion) portions of the package that can be directly applied to the Daya Bay reactor cores and used to predict the fuel cycles and isotopic fission rates. For his thesis, Dr. Seilhan developed a stand alone software package to study near site physics potentials for the Daya Bay experiment. In addition, he studied our sensitivity to reactor refueling shutdowns and investigated potential IBD rate cross checks that can be extracted from core-off data.

As another example of past student contributions, Prof. White and Mr. Vals (an undergraduate physics student) studied the thermal properties of the antineutrino detectors and water pools using a commercial FEA program, FLUENT [34]. These thermal studies appear in the Daya Bay Technical Design Report (TDR) and have influenced a variety of design decisions.

Ms. Emily Draeger is a fourth-year grad student. Her contributions thus far have been development of simulation tools and participation in detector construction. While on-site, she was selected to join the AD filling team, charged with carefully and systematically filling the AD with mineral oil, liquid scintillator (LS), and Gd-doped LS. She was a detector filling expert and was required to travel to Daya Bay whenever an AD was filled. Her software projects involve updating the electronic simulations to include the energy sum circuit in the PMT readout chain. Ms. Draeger added the correct shaping function into the simulation, and also updated the simulation to include missing features. Another component that was missing in the simulation was the FADC (fast analog to digital converter). The FADC allows us to read out the energy sums from pairs of boards without shaping and with 1 GHz sampling resolution.

Mr. Jose de Arcos only recently joined the group and did not made significant contributions during the grant period, although he has taken shifts and has been learning the software and code systems.

MINOS

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The Main Injector Neutrino Oscillation Study experiment (MINOS) examines neutrino oscillations using a ν_μ or $\overline{\nu}_\mu$ beam produced within the Neutrinos from the Main Injector (NuMI) beamline. It consists of two functionally identical calorimeters. The 0.98 kton near detector is located approximately 1 km from the NuMI target, and the 5.4 kton far detector is located 734 km further downstream in the Soudan Mine Underground Lab in northern Minnesota. In the standard configuration, the Low Energy (LE) Forward Horn Current (FHC) neutrino beam was comprised of 91.7% ν_μ , 7.0% $\overline{\nu}_\mu$ and 1.3% ν_e and peaked in energy around a few GeV. With the horn polarity reversed (RHC) the beam was 39.9% ν_μ, 58.1% $\overline{\nu}_\mu$ and 2.0% ν_e. NuMI operated in LE mode beginning in May 2005, and completed the first dedicated oscillation measurement using a $\overline{\nu}_\mu$ beam in 2010.

MINOS measures the atmospheric oscillation parameters Δm^2_{32} and $\sin^2(2\theta_{23})$ by measuring the probability that a given muon neutrino will oscillate while it travels between the near and far detectors. MINOS currently has the world's most precise measurement of Δm^2_{32}, $(2.32 + 0.12 - 0.08) \times 10^{-3} eV^2$ [35], and the only measurement of $\Delta\overline{m}^2$, $(2.62 + 0.31 - 0.28(stat.) \pm 0.09(syst.)) \times 10^{-3} eV^2$ [36]. MINOS data have also been used in the hunt for the mixing angle θ_{13}; however, only an upper limit on this value was achieved, $\sin(2\theta_{13}) < 0.12$ in the normal mass hierarchy and $\sin(2\theta_{13}) < 0.2$ in the inverted hierarchy at 90% C.L. [37] . The experiment has also been used to study cosmic rays [38] and a variety of esoteric topics such as warming of the upper atmosphere [39] and Lorentz invariance [40].

IIT has a long history of accomplishment on MINOS. In recent years, Prof. White and Dr. Graf (a post-doc) each have served as co-run coordinator for MINOS (1-year terms for each). Dr. Graf was also the on-call near detector electronics expert for two years. Prof. White served as a near detector construction and installation manager, and Prof. Rubin (now retired) supervised and managed the farming of MINOS data for years. IIT personnel have contributed to a number of analysis projects and service tasks, including cross-talk studies, detector calibration, and a number of non-oscillation related physics results. The final analysis topic underway by IIT personnel involves a study of quasielastic events in the Near Detector. Prof. White has been serving as shift coordinator (a service task that he has continued after ending his term as co-run coordinator) and is served on the internal paper committee for an improved analysis of $\overline{\nu_\mu}$ disappearance.

A comparison of MINOS Near Detector data to the default NEUGEN model for quasielastic (QE) CC events and their backgrounds shows three distinct trends. The model underpredicts the rate of QE events relative to the total. The data show more events than the model predicts in the intermediate $0.2 < Q^2 < 1.2$ GeV^2 region. Finally, the model overpredicts the number of QE events at very low momentum transfer, $Q^2M < 0.20$ GeV^2.

It is adequate to adjust the effective axial-vector mass M_A^{QE} to a higher value to account for the first two effects. This parameter is an effective parameter in the sense that we are likely using to account for nuclear effects in iron rather than measuring an unexpected shape of the axial-vector form factor. The very low momentum transfer region for neutrino interactions has been very hard to describe. For all three canonical interaction types, elastic and quasielastic, resonance production, and deep inelastic scattering (DIS), this region is singled out as difficult or impossible to model.

When first confronted with a poorly modeled very-low Q^2 spectrum and no theory guidance, we started by tuning a Pauli-suppression factor. When the resonance decayed to a nucleon and one or more pions, we looked at the nucleon momentum and when it was below a tunable k_{Fermi} value the interaction was suppressed. This is how, using NEUGEN, we treat quasielastic interactions in the Fermi-gas model. This procedure is extremely poorly motivated and unphysical for resonance interactions, which is the dominant background, and is believed to be the most severely mis-modeled part of the current event generators' cross section model. Indeed, the very low Q^2 discrepancy is seen very strongly in resonance interactions.

Dr. Graf has been formulating an alternative description of the very low Q^2 discrepancy for resonance interactions. Even though it is unphysical, the Pauli-suppression approach was used to formulate a bin by bin description of the suppression using two different resonance dominated background selections fit separately for k_{Fermi}. Virtually identical suppression shapes were derived from each selection. The average was fed back into the re-weighting scheme and tuned by refitting the two selections. The standard quasielastic analysis will then be repeated with the alternative resonance suppression. This is a work in progress and has not yet been through the "blessing" procedure to be shown outside the collaboration.

An additional systematic that needs to be addressed for the quasielastic analysis to be considered finished is the track angle resolution. This is necessary since the reconstructed energy for quasielastic events depends significantly on the reconstructed muon track angle. Dr. Graf has been working on a study to do this by dividing the reconstructed muon track into upstream and downstream segments. Each segment is then refit separateley and the angles of the two segments compared.

A paper draft of this work should be ready for internal distribution by the end of the calendar year. Dr. Graf will end his association with MINOS after the publication of this work.

Double Chooz Reactor Experiment

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The major emphasis of the DOE-supported Double Chooz effort at IIT was detector calibration, key to achieving the θ_{13} sensitivity goal. The IIT group developed an LED flasher that can be lowered along the detector z axis and used for photomultiplier-tube (PMT) calibration. Chemical compatibility with the gadolinium-loaded liquid scintillator used in the Double Chooz Neutrino Target drives the need for a hermetically sealed, chemically inert flasher vessel. The flasher circuit is battery-powered so as to avoid the need for external electrical connections and vessel penetrations. Our first prototype was housed in a vessel consisting of an acrylic cylinder and stem with a Teflon plug and a $2''$-diameter Teflon diffuser ball, to be lowered into the Target vessel on a Teflon-jacketed cable. The acrylic stem proved insufficiently strong for reliable compression of the Teflon O-rings that provided the seal. However, that prototype was used to obtain a first measurement of PMT time offsets before the filling of the far detector. Our second flasher prototype featured an all-Teflon vessel (eliminating the troublesome seal between the cylinder and the diffuser), with diffuser diameter increased to $3''$, since our tests of the first prototype at Argonne showed that its light output was less uniform over solid angle than desired. However, light emitted from the cylindrical portion of the vessel caused excessive anisotropy in polar angle. Our final design (Fig. 4) employs a black Delrin cylinder housing the battery and circuit board, with a Teflon or white Delrin diffuser, Delrin having been recently added to the list of materials certified for use.

Kaplan continues to participate and to supervise an IIT graduate student, Guang Yang, on Double Chooz with a modest grant from Argonne National Laboratory. Mr. Yang is just starting to climb the learning curve and will be working closely with Argonne's Dr. Zelimir Djurcic on calibration and physics analyses.

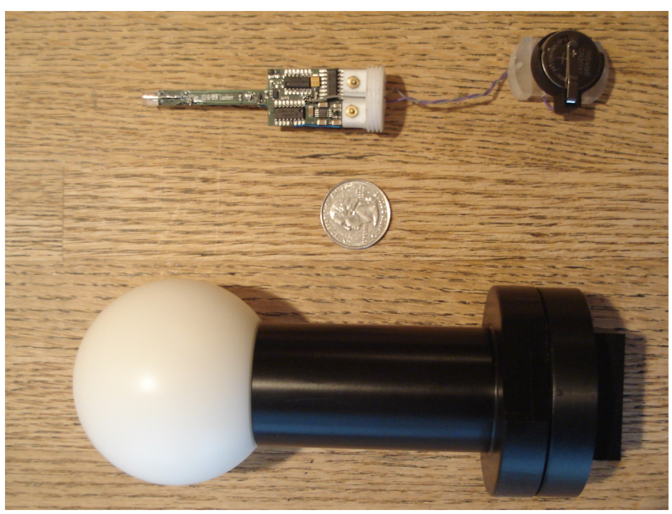

Figure 4: Photo of final LED flasher prototype.

Antiproton Initiative

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The Fermilab Antiproton Source is the world's most intense and (for now and some years into the future) highest in energy. Now that Tevatron running is ended, it can be used for exciting antiproton-beam fixed-target physics, as well as to significantly broaden Fermilab's near-term program at relatively modest cost. Prof. Kaplan has been leading the exploration [41] of the physics potential of the Antiproton Source, inspired initially by the desire to follow up on the world-leading sensitivity to new physics in hyperon decay achieved in the HyperCP experiment, on which the IIT group collaborated.

Over the past few years, Kaplan led and put a great deal of effort into the development of a pair of relatively modest proposals for new experiments at the Fermilab Antiproton Source. Unfortunately, we were unable to overcome the entrenched opposition of Fermilab Director Pier Oddone, and these efforts have been suspended.

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