Research in Elementary Particle Physics
University of Texas at Arlington

The High Energy Physics Group at the University of Texas at Arlington proposes a three-year program of research in the Energy and Intensity Frontiers, and in Detector Research and Development. We will continue our long term strong role in the ATLAS experiment, continue our ramp up of Intensity Frontier effort, prepare for long term participation in the International Linear Collider, and to increase our detector R&D efforts in pursuit of new innovations.

The ATLAS group at UTA proposes to continue our physics studies in the areas of Higgs and SUSY. We have significant detector responsibilities, including TileCal management in support of UTA-built sub-detectors and components, Phase I commissioning and operations, and HL-LHC R&D and construction projects. We have new responsibility for the construction of more than 1000 newly developed Low Voltage Power Supplies, while continuing R&D work on the TileCal Trigger/DAQ Preprocessor Boards. We will maintain our leading roles in ATLAS Distributed Computing (ADC) software development and operations, leadership in U.S. ATLAS computing, operation of the SouthWest Tier-2 center, and analysis support.

The full exploration of the Higgs sector, the role of the top quark in the Standard Model, and the search for new physics, require high precision measurements of an e+e- collider in combination with the energy reach of the LHC. We propose to continue our leadership role in the SiD Detector Consortium: detector design, specification of subsystems, physics studies (particularly in response to new results from the LHC), machine-detector interface issues, and detector simulation. Activities at UTA will include the design and specification of the scintillator/steel hadron calorimeter and its full simulation, as well as service on national and ILC committees.

The Intensity Frontier group at UTA pland to contribute to the Fermilab Short-Baseline Neutrino (SBN) program as well as the Long-Baseline Neutrino (LBN) program. The LBN program has chosen the liquid argon time projection chamber (LArTPC) detector as its technology of choice to be used in the Deep Underground Neutrino Experiment (DUNE). DUNE aims to address the questions of the neutrino mass hierarchy and CP-violation in the lepton sector. The SBN program aims to conclusively address the experimental hints of sterile neutrinos through the utilization of three LArTPC detectors: the Short-Baseline Near Detector (SBND), the Micro-Booster Neutrino Experiment, and the ICARUS Experiment. All three of these SBN experiments as well as DUNE are strategically selected to leverage the UTA expertise in LArTPC technology across them.

The detector research and development consists of two main thrusts. The first thrust is lead by Brandts research into the characterization and development of long-life microchannel plate (MCP) photomultiplier tubes (PMTs), capable of high rates. We propose to continue the ongoing work to optimize lifetime testing methods, expedited lifetime measurements, and after- pulsing studies that seek to correlate lifetime with the amount of specific heavy ions through utilizing the UTA Picosecond Test Facility. The second thrust will be lead by Nygren along with new faculty Jones and Asaadi in projects to develop large area light detecting plates using wavelength shifters and SiPMs that can be deployed in noble gas or liquid TPCs. These devices will be tested within an existing high purity xenon gas system and within liquid argon to understand the energy resolution and position dependent response. Applications include any TPC-related experiments where good light collection efficiency is needed, ranging from high priority neutrino physics experiments to neutrinoless double beta decay experiments.

RESEARCH IN ELEMENTARY PARTICLE PHYSICS

A PROPOSAL TO THE U.S. DEPARTMENT OF ENERGY

THE UNIVERSITY OF TEXAS AT ARLINGTON

Physics Department, 502 Yates Street, Arlington, Texas 76019, USA.

Lead Principal Investigator:	Andrew P. White (817) 272 2812 awhite@uta.edu
Co-Principal Investigator:	Kaushik De
Co-Principal Investigator:	Andrew Brandt
Co-Principal Investigator:	Jaehoon Yu
Co-Principal Investigator:	Amir Farbin
Co-Principal Investigator:	Haleh Hadavand
Co-Principal Investigator:	Jonathan Asaadi
Co-Principal Investigator:	David Nygren
Co-Principal Investigator:	Benjamin Jones

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FOA number: **DE-FOA-0001604**

DOE/Office of Science Program Office: **High Energy Physics**

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PAMS Letter of Intent tracking number: LOI-0000014874

Research Subprograms:
Experimental Research at the Energy Frontier in High Energy Physics
Experimental Research at the Intensity Frontier in High Energy Physics
Detector Research and Development in High Energy Physics

Cover Page Supplement

List of Research areas:

- **Energy Frontier PI's:** Andrew Brandt (50%), Kaushik De, Andrew White, Jaehoon Yu, Amir Farbin, Haleh Hadavand
- **Intensity Frontier PI's:** Jaehoon Yu, Jonathan Asaadi
- **Detector Research and Development PI:** Andrew Brandt (50%)

Lead PI: Andrew White

The numbers below are OLD - will be replaced with the 2017-20 values

	Name	Research Area	Year 1 Budget	Year 2 Budget	Year 3 Budget	Total Budget
Lead-PI	Andrew White	Energy Frontier	$165,589	$162,762	$168,261	$496,612
co-PI	Andrew Brandt	Energy Frontier	$180,190	$188,578	$186,387	$555,155
co-PI	Kaushik De	Energy Frontier	$234,204	$234,204	$241,351	$709,759
co-PI	Amir Farbin	Energy Frontier	$0	$102,645	$106,245	$208,890
co-PI	Haleh Hadavand	Energy Frontier	$89,018	$87,920	$92,073	$269,011
	Total	Energy Frontier	$669,001	$776,109	$794,317	$2,239,427
co-PI	Jaehoon Yu	Intensity Frontier	$49,468	$102,645	$106,245	$258,358
co-PI	Jonathan Asaadi	Intensity Frontier	$107,098	$107,098	$110,876	$325,072
	Total	Intensity Frontier	$156,566	$209,743	$217,121	$583,430
co-PI	Andrew Brandt	Detector R&D	$87,998	$87,998	$90,831	$266,827
	Total	Theoretical Research	$87,998	$87,998	$90,831	$266,827
	Grand Total	**All areas**	$913,565	$1,073,850	$1,102,269	$3,089,684

Table 1: Name and Yearly Budget for Proposals with Multiple Research Areas.

Part I
UTA Group Introduction

UTA Group Introduction

Research at the Energy Frontier

put introduction to Energy Frontier here.....

Summary for PI Dr. Andrew P. White

Accomplishments

- Founder of UTA High Energy Physics Group 1991
- Inventor of the DZero Experiment Intercryostat Detector
- Inventor of Gas Electron Multiplier (GEM) based Digital Hadron Calorimetry
- American Physical Society Fellowship - 2011
- Recipient of UTA Distinguished Record of Research Award, May 2009
- Spokesperson for the SiD Detector Concept for the International Linear Collider (2010-)
- Chairman of the Physics Research Council for DESY, Hamburg/Zeuthen, Germany (2012 2015)
- Member of the U.S. Department of Energy National Reviews of Detector Research and Development at National Laboratories, 2009, 2012
- Served on national review committees and was a member of the Department of Energy, HEPAP Subpanels on the Future of Particle Physics in the United States (1998 and 2007)
- Member of the ECFA Detector Panel (2012-2016)
- Member of the ATLAS Tile Calorimeter Speakers' Committee (2014-)
- Member of the US ATLAS Analysis Support Group
- Universities Representative on the Americas Linear Collider Committee (2012-)
- N. American representative for the CALICE (Calorimetry for Linear Colliders) Collaboration
- Member of the Management Board for the Micro Pattern Gas Detector Collaboration/CERN, RD-51
- Instigator and original leader of the DZero Experiment New Phenomena physics group
- Co-designer of the ALEPH (CERN) Experiment Inner Trigger and Tracking Chamber (1982-4)
- Invited to lead numerous physics and detector working groups at large national and international high energy physics meetings

Milestones

- FY16 - Publish Run 1 results from Higgs to invisible decays analysis - done.
- FY17 - Publish Run 2 2015-16 results from Higgs to invisible decays analysis.
- FY17 - Take on new graduate student for Higgs/invisible analysis, ITC qualification tasks.
- FY17 - Complete study of ITC E-cells new segmentation, energy resolution study.
- FY17 - Complete full simulation of SiD AHCAL, barrel + endcaps.
- FY17-18 - Develop design of SiD AHCAL barrel module.
- FY17-18 - Complete plans for ATLAS ITC Tile/Fiber replacements in LS2.
- FY18-19 - Co-convene the full Run 2 Higgs to Invisible analysis.
- FY18-19 - Prepare (with ATLAS Tile Institutes) tile/fiber assemblies for installation in LS2.
- FY18-19 - Expand SiD Consortium in preparation for drafting SiD Technical Design Report.
- FY18-19 - Begin first draft of SiD Technical Design report.
- FY19 - Publish result for Run 2 Higgs to Invisible analysis, possible interpretive paper(s).
- FY19 - Contribute effort to installation and testing of the new ATLAS ITC E-cells.

Plans

With the discovery of the Higgs boson great opportunities exist for understanding this fundamentally new state of matter, and for discoveries associated with existence. In this regard, I am committed to the continuing success of the ATLAS Experiment's physics program through analysis of current and future data in the search for invisible decays of the Higgs, and through support work on the Intermediate Tile Calorimeter, and data quality validation shifts. Taking on a new graduate student, I will continue our study of the optimal segmentation of the new ITC E-cells. I will work to identify suitable replacement ITC tile and fiber materials and provide expertise in their installation and re-commissioning. I will work on the extension of the VBF-Higgs to invisible analysis, and paper publication, using existing data and, with my student, I will develop analysis strategies for analyzing the 14 TeV data accumulated at high instantaneous luminosity and pileup. The full exploration of the Higgs sector will require precision studies of couplings at the percent level or below. The best prospect for achieving such precision measurements in the foreseeable future lies with the International Linear Collider. As Spokesperson for the SiD Detector Concept for the ILC, I will continue to lead its development and promote its realization within the global HEP community. I will work towards securing a U.S. role in the ILC project in Japan and develop the site-specific implementation of SiD at the selected Kitakami location. With the SiD Executive Committee and the Institutional Board, I will create the team that will produce the SiD Technical Design Report over a 2-3 year period, and guide the process of subsystem technology selections. I will represent SiD on the Linear Collider Physics and Detectors Executive Board, and the Americas Linear Collider Committee, and with interactions with funding agency(s). I will work to build the SiD Collaboration in all regions. Locally at UTA, I will pursue the implementation of scintillator/SiPM hadron calorimetry for SiD, together with its full simulation.

PI Summary: Kaushik De

PI Summary: Andrew Brandt

PI Summary: Haleh Hadavand

Postdoc: I started my postdoc position with Southern Methodist University on the ATLAS experiment. I joined the online monitoring software effort at CERN and within a few months developed a histogram naming system for the online histograms and modified an existing/decommissioned software for histogram collection to work properly within a new release. I also started designing and laying down the foundations for the ATLAS data quality monitoring system. I was one of the main visionaries, designers, and developers for this system which is still used both online and offline by ATLAS. My main development contribution was the plug-in algorithms that could be loaded at any point into the system, the online display, and the online time series analysis [**?**, **?**].

During commissioning of cosmics before LHC collisions I setup the entire online monitoring chain from histogram production to final DQ assessments of monitoring data. This required thorough understanding of the offline software, within the High Level trigger, and the online environment, software, and tools. I was the first to develop software to produce η vs ϕ plots of clusters within the LAr and Tile calorimeters online, use the gatherer to collect histograms from various monitoring nodes, display the histograms, apply DQ, and time series assessment of the data quality information. This work gives me a very thorough understanding of the monitoring system on ATLAS both online and offline.

I joined the UED diphoton + Missing Et analysis group for early data taking since the analysis would produce more stringent results with as little as 10 pb^{-1} of data. With a small analysis team we had one of the first 20 published papers out of the ATLAS experiment [**?**]. I was interim editor of this paper and also presented alternative methods of MET calculations for the experiment in addition to being main contributor to the analysis.

After publishing the UED results I started analysis on Randall Sundrum Gravitons to diphotons where I implemented both a Frequentist tool for setting limits and setup the Bayesian code with BAT for the final limits. I was also one the of main analysers in the group. I was a co-editor for the resulting conference note and paper [**?**, **?**].

Research Faculty and Assistant Faculty: Since I joined UTA in July 2012 I have been working on the charged Higgs to $\tau^+\nu$ in fully hadronic final states. I have been part of two conference results and two publications [**?**, **?**, **?**, **?**]. My role on the Run 1 measurement was the high mass background estimation of the $\tau \to$ jets background and the statistical treatment leading to the final limits for the analysis. I produced Run 2 projections for this analysis and determined that with only a few $fb^{-1}$of data evidence of signal can be observed. I also produced the first intermediate mass samples for the charged Higgs in the mass range of 160-180 GeV. This was work done with collaboration with theorists to reconcile interference terms in this region. For the Run 2 analysis I motivated using the MET trigger instead of the tau+MET trigger used in Run 1. This choice greatly reduced the trigger and background systematics. The background suffered from low statistics when using the tau+MET trigger since the trigger imposed a medium tau selection. Therefore the matrix method was a comparison of medium versus tight tau selections where with an MET trigger one could use loose versus tight tau selection hence increasing the statistics. I also motivated the control region selection for performing the fake factors method and as a cross check performed a template fit to determine the QCD background [**?**, **?**]. My work on this charged Higgs final state has resulted in my appointment to the charged Higgs convenership position thereby overseeing all charged Higgs activities on the ATLAS experiment.

As charged Higgs convener I have motivated new charged Higgs final state searches. One of these channels is a decay to SUSY final states which would have a signature of three leptons plus missing ET. Two of these leptons would be same flavor and opposite sign. Several independent evidence of an excess in multi-lepton events have been reported on the ATLAS experiment [**?**]. I have recently produced MC samples for this final state using Madgraph and will distribute to analysers to see if the data is consistent with a charged Higgs signal. I have also produced samples for $H^+ \to$ WZ with final stats of qqll, lvqq, and qqqq. There are existing analyses that have the same final states as the ones mentioned so a search for charged Higgs signal can be performed fairly quickly.

In April 2016 I was appointed to the position of charge account manager (CAM or L3 manager) for the low voltage power supplies (LVPS) for the Tile calorimeter for HL-LHC. This account will manage about $1 million of labor, travel, and materials and supplies over a 6 year period. I have been working closely with Andrew Brandt, the institutional representative for UT Arlington, on this project. More details about this project are highlighted in section **??** and the schedule is detailed in table **??**.

- FY16 - Publish results for charged Higgs on 2016 dataset including the tau-lepton channel.
- FY16-17 - Design of Tile LVPS elevated temperature test stand (burn in station).
- FY17 - Fabrication of Tile LVPS burn in station.
- FY17 - Publish charged Higgs results using τ polarization.
- FY17 - Take new graduate student for Z+X analysis.
- FY17 - Hire new postdoc to work on charged Higgs and Z+X analyses.
- FY17-18 - Develop di-tau reconstruction algorithm.
- FY18 - Develop analysis suite for Z+X analysis.
- FY18 - Publish Z+X results using Higgs mass constraint.
- FY18 - Publish charged Higgs results using deep learning techniques for selection and/or tau

reconstruction.
- FY18-19 - LVPS V8.2 prototype.
- FY18-19 - Testing and integration of LVPS into vertical slice test.
- FY19 - Charged Higgs results with Matrix Element Methods.
- FY19 - Graduate student Akafazade graduates on charged Higgs analysis.

Part II
The ATLAS Experiment

Faculty PI: Kaushik De, Andrew Brandt, Andrew White, Amir Farbin, Haleh Hadavand

The UTA HEP group joined the ATLAS collaboration in the early days of planning for the experiment, 21 years ago. Since then, we have participated in every aspect of the experiment: design, construction, commissioning, computing, management, and physics analysis. The impact of the work done by our group has benefited every aspect of ATLAS, and led to the successful physics program of the experiment. Currently, our group has N active members in ATLAS, which makes UTA one of the largest university groups in ATLAS. We have an excellent record of synergistic accomplishments among the members of our group, and among the various externally funded projects. While the DoE base program supports less than one third of our activities in ATLAS, the impact of this funding is magnified many fold in advancing the mission of the core physics goals of the DoE.

Currently, the participation of the UTA group in ATLAS is managed by 4 FTE effort among 5 PI's. In Table **??**, we show the fractional contribution of each PI to experiments at the Energy Frontier.

		2017	2018	2019
ATLAS	Kaushik De	1.0	1.0	1.0
	Andrew Brandt	0.5	0.5	0.5
	Andrew White	0.5	0.5	0.5
	Amir Farbin	1.0	1.0	1.0
ILC	Haleh Hadavand	1.0	1.0	1.0
	Andrew White	0.5	0.5	0.5

Table 2: Fractional level of effort for each PI by research area within the Energy Frontier.

Physics at ATLAS

1 Higgs Physics (PI: Brandt, Hadavand, White)

On July 4, 2012 ATLAS and CMS announced the observation of a new particle consistent with a Standard Model (SM) Higgs Boson [**?**,**?**], ending the 50 year search for the elusive final SM particle. This landmark discovery fulfills the prime objective of the LHC by providing evidence for a Higgs field that gives mass to fundamental particles through their coupling to the field thus uncovering the mechanism for electroweak symmetry breaking. This Higgs-like particle weighed in with a mass of about 126 GeV, and had the highest significance and best mass resolution in the $\gamma\gamma$ and the

ZZ decay channels. UTA had many contributions to the Higgs discovery, including critical roles in computing, detector building (ITC), and commissioning (ITC, MBTS, trigger).

Although the SM has been extremely successful at explaining electroweak data, so-called problems with the theory, such as the quadratic divergence of radiative corrections to the Higgs mass (a.k.a. the Hierarchy problem), and unanswered questions, such as the nature of dark matter, drive our search for new phenomena at the TeV scale. We have strong arguments (i.e. naturalness and the "dark-matter miracle") that solutions to these problems and questions may be found at this energy. The leading theoretical solution is Supersymmetry (SUSY) since it not only addresses the hierarchy problem, but can also provide a dark matter candidate and predicts the unification of gauge couplings at the Grand Unified Theory (GUT) scale. We also know that the uncertainty of the current Higgs measurements allow for non-SM decays of the Higgs boson of 26% [**?**] and that theories with SM+singlets have equivalent level of branching fraction [**?**].

With the discovery of the Higgs and reasons eluminated above the UTA groups focus has shifted to BSM Higgs phenomena in three fronts: A charged Higgs search in the $\tau\nu$ final state, invisible Higgs search in the VBF channel, and new propsal by Hadavand in the search for Z+X channels. The charged Higgs group is led by Brandt and Hadavand overseeing the work of post-doc Justin Griffith and Hadavand's student Hussein Akafzade. Both Hadavand and Griffith have leadershop roles in charged Higgs as the charged Higgs convener and analysis contact for the $\tau\nu$ final state. Akafzade's thesis will be based on the Run 2 dataset of $100 fb^{-1}$ on charged Higgs. By mid-2017 Hadavand will take a new student who will work on the Z+X analysis together with a newly hired postdoc working on both charged Higgs and Z+X.

1.1 Charged Higgs (PI: Brandt, Hadavand)

Brandt and Hadavand will continue the search for charged Higgs in fully hadronic final state of $\tau^+\nu$. The discovery of charged Higgs would be a clear sign of BSM physics and would imply that the 125 GeV Higgs is part of a more complex Higgs sector. The Charged Higgs is predicted by several models such as ones with Higgs triplets and Two-Higgs-Doublet-Models(2HDM) [**?**,**?**,**?**]. In the MSSM, which is a type II 2 Higgs Doublet Model (2HDM), the main decay of charged Higgs at the LHC is t $\rightarrow$ b H^+ for H^+ mass below m_{top}. At charged Higgs masses above m_{top} the main production at the LHC is in association with a top quark. In the MSSM the Higgs sector can be completely determined by the H^+ mass and tan β, the ratio of vacuum expectation values of the 2HD. For masses below the top mass the $\tau\nu$ decay is dominant for $\tan\beta > 2$.

Hadavand motivated and was responsible for investigating new models for analyzing the intermediate mass region of 160-180 GeV. Only recently have theorists been able to reconcile $t\bar{t}$ interference effects supply us with NLO calculations of the cross section as a function of mass and $\tan\beta$. The addition of this mass region will close the gap mH vs $\tan\beta$ mass range and also produce competitive results at low $\tan\beta$ vs A $\rightarrow \tau\tau$ and $H^+ \rightarrow t^+$b. The measurements for this region will be performed by the end of 2016.

Griffiths and Hadavand have led the charged Higgs search with Griffith being the analysis contact and Hadavand the charged Higgs convener. Under their leadership UTA group has produced the final results including plots and statistical interpretation, estimation of the systematic uncertainties, including theoretical, writing the analysis code, production of common ntuples, and trigger studies (with Jae Yu's student Last Feremenga). By using simulated $t\bar{t}$data instead of τ embedding we were able to publish results with 3.2 $fb^{-1}$of data and a conference note at $14.7 fb^{-1}$of data at 13 TeV. This luminosity increase increased the mass reach of the analysis from 250 GeV in Run 1 to 600 GeV in Run 2. The jet to tau background statistics for the Run 2 analysis were vastly improved over Run 1 by using Hadavand's suggestion of only using a missing ET trigger as opposed

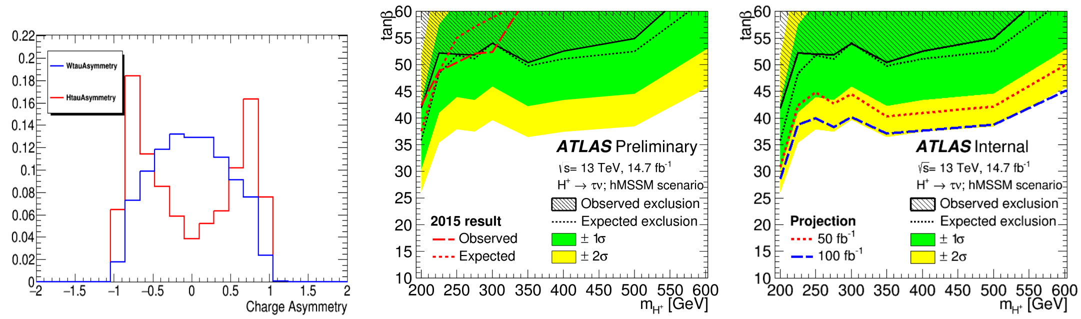


Figure 1: Distribution of τ polarization for Higgs and W decays, left; ICHEP 2016 hMSSM exclusions including 2015 exclusion, middle; ICHEP 2016 hMSSM exclusions with $50fb^{-1}$ and $100fb^{-1}$ of data projections.

to a tau plus missing ET trigger. The use of the tau in the trigger implied that a medium selection of taus had to be used in the fake factor method, where in Run 2 we could use a Loose selection therefore greatly enhancing the statistics.

As we can see from figure blah with the 2018 dataset of 100-150 Gev of data we are still only excluding large $\tan\beta$values so this analysis continues to be an important measurement as we accumulate more data. We have plans to apply techniques to improve the analysis' sensitivity over it's early Run 2 predecessor. The tasks aimed for these improvements are listed below:

Use tau polarization to reduce true tau background ; Akafzade The tau polarization can be used to separate the W $\rightarrow\tau\nu$ background from the signal. The intrinsic polarization of W$^+$ is -1 while that of H^+ is +1. The tau polarization is defined as $P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$. A plot of the charge asymmetry, defined as $\Upsilon = \frac{p_T^{track}}{p_T} - 1$, is shown for the signal and background in the $\tau \rightarrow \rho\nu_\tau$ final in figure **??**. Other 1-prong decays will also have similar separation in the charge asymmetry. The 1-prong decays can be separated from the 3-prong decays in the final fitting machinery and added statistically together. This variable will be used as additional variable to the fit in the 1-prong case.

Use matrix element method to reduce true tau background ; Hadavand, Akafzade In addition to the tau polarization one can utilize the event kinematics by utilizing the matrix element method to distinguish the signal from the true tau background originating from $t\bar{t}$events.

By looking at the distribution $d(x) = \frac{P_S(x)}{P_S(x) - P_B(x)}$ where P_S and P_B correspond to the weights from the signal and background hypothesis. I have performed initial tests with MadWeight for achieving this goal. This variable can then be added as one of the variables in the BDT.

Use boosted decision trees ; Postdoc and Akafzade As mentioned earlier for early Run 2 results the discriminating variable used in the fit was m_T. As an alternative we can incorporate several variables into a bdt and use that output as the discriminating variable in the fit machinery. Some variables that have been investigated in some preliminary studies are m_T, leading b jet p_T , τp_T, MET, $\Delta\eta(\tau-$leading jet), $\Delta\phi(top-$sub-leading jet).

Determine jet $\rightarrow\tau$ Background from Control Region ; Hadavand, Akafzade For Run 1 the systematics for the τ $\rightarrow$jet background were one the largest in the analysis. Due to low statistics at the high mass a fit above 200 GeV was necessary to get an estimate of the background in that region. This is important since this is the dominant background in the high mass region and without a background model the limit machinery would fail. As an alternative to the matrix method used for the Run 1 published paper one can use a control region with no signal and loosen the selection criteria to introduce more fake taus. This can be done by requiring a zero bjet region and only requiring a loose tau selection. The normalization of this background can then be derived within the fit to data. This should reduce both the statistical and systematic uncertainty of the analysis. The use of the tau plus MET trigger has caused some of the main issues with statistics for the QCD background in Run 1. I proposed to use a MET trigger which actually had higher efficiency than the tau plus MET trigger. The use of this trigger increases the statistics for the background estimation.

Apply Deep learning techniques for selection; Brandt, Farbin, Hadavand, graduate and undergraduate students The deep learning technique can be applied to this analysis in two ways. One way would be to use it to distinguish $t\bar{t}$background from the signal by training on those samples. Another way to apply deep learning would be in the tau reconstruction in place of the BDT technique which is used now. We plan to use Farbin's extensive experience in the field of deep learning to help with us with this effort.

Optimize Binning for Limits ; Postdoc, Akafzade The low statistics in the tail of the distribution has made the $\mathrm{H}^+ \rightarrow \tau\nu$ channel difficult for setting limits. In many cases we found that several systematic variations performed for pull determination would make the fits fail. This has to do with the fact that the data has low stats and is spiky since similar statistics in smooth MC did not cause the same failures. By making requirements on signal over background and the number of total background in a given bin and then testing with pull estimation I was able to optimize the best binning for both stability and sensitivity. For performing projections to higher luminosities we also had to extrapolate the background to the higher masses to determine a realistic scale of the background in this region. After performing the extrapolation we could re-optimize the binning for the given luminosity projection, a technique developed by Hadavand.

1.2 Z+X Scan (PI: Hadavand)

The increased beam energy and intensity in the LHCs Run 2 and 3 will likely provide the best opportunity to discover BSM physics for at least the next ten years. The task of discovering it, however, can be more challenging compared to the SM Higgs, whose mass was well constrained by precision electroweak data and the underlying theory, i.e. the SM, was well understood and extensively tested for over half a century [**?**, **?**, **?**, **?**]. In contrast, the number of theories and models that motivate BSM Higgs searches are significantly larger and more speculative, requiring that a much wider net be cast to cover a broader range of masses and final states.

Hadavand proposes to perform searches using the 125 GeV Higgs to bootstrap her way to search for new exotic decays of the Higgs or other BSM states. The Higgs mass constraint will help aid the search for signal in a specific region. This method is motivated but not limited to the final states listed in table **??**. The search can be further expanded in a model-independent manner by scanning for Z+X where X can be of masses not theoretically motivated. This proposal combines a search within five theoretical models each decaying to ll$\tau\tau$ and/or $\tau\tau$ll, thereby using our extensive experience with τ leptons. With one analysis we are able to cover all of these models thereby increasing the analysis reach.

The Z+X search will primarily probe SUSY models for example Next-to-Minimal Supersymmetric Standard Model (NMSSM) that include an additional scalar singlet or SM +singlet models. It can also be used to discover other states not theoretically motivated therefore investigating new mass regions where potential new particles could exist. Additionally I propose searching for a "dark" Z in the mass range $12 <$ m< 60. A "dark" Z serves as the mediator of a new U(1) gauge symmetry that can serve as the portal to a hidden sector that constitutes dark matter [**?**].

Analysis	Channels $\rightarrow$	$\tau\tau$ ll	ll $\tau\tau$	Theory
Z Scan	$h \rightarrow ZZ^*$	✓	✓	SM
	$A \rightarrow Zh$		✓	MSSM, NMSSM
	$h \rightarrow$ ZZ(dark)	✓	✓	dark U(1) gauge
	$X(h) \rightarrow Za$ for a l=μ	✓	✓	NSSM, SM+singlet

Table 3: Table showing channels and accessible final states and theoretical models for several BSM models including the standard model h $\rightarrow$ZZ* channel [**?**]. The mass of the scalar singlet a and Z(dark) are $4 < m(a) < 10$GeV $15 < m(Z(dark)) < 60$GeV respectively.

My strategy is to combine several final states and channels to increase statistics and look for a bump using a bump-hunting procedure I developed as a first pass. The approach removes the need for setting limits in a fine granularity in the discriminating variable, thereby greatly speeding up the statistical analysis. This speedup will allow for quicker turn around of searches in the absence of signal. In the end the full statistical treatment as recommended for ATLAS will be performed to present the final results but this first pass will allow for flexibility in the search.

For the Z mass scan I propose to perform two mass scans constraining the given particle combination to the Z mass and scanning in the 'other' particle. For example, Z(ll) other($\tau\tau$) and Z($\tau\tau$)other(ll) would be two separate scans of the 'other' particle after requiring that the event has a Z particle. The mass range of the scan would go from 4 GeV to 2 TeV and each object would be a resonance in that mass spectrum. The ee and $\mu\mu$ channels are added together in one spectrum since they have similar resolution and hence can increase the statistics for bump-hunting. The two scans, one with taus and the other with l=μ,e can then be combined together with a statistics framework. Of course the 4 lepton final state is one that is extensively tested for the SM ZZ* final state. This analysis would add the ll$\tau\tau$, $\tau\tau$ll final states to this channel for the first time. The resolution will not be as favorable as the 4 lepton final state but by constraining the on shell Z to decay to $\tau\tau$ one can improve the mass resolution. These final states can add further sensitivity to this channel specially as the LHC gathers more data. With about 10 fb^{-1} of data at the center of mass energy $\sqrt{s}$ = 13 TeV the 4 lepton analysis observed 3 events per category including a combination of electrons and muons. The efficiency for tau reconstruction is lower (30-40% as opposed to around 80%) than the electron and muon channels and in addition pose a more challenging final state due to the existence of neutrinos. However on average $35/80 \times 4 \sim 2$ $(2\tau 2e, 2\tau 2\mu, 2e2\tau, 2\mu 2\tau)$ events/10fb^{-1}can be added to this channel [**?**] increasing the total statistics by 2/12=17%. With a final dataset of 150$fb^{-1}$of data this would be a significant addition to the existing channels.

By scanning for particles after selecting the Z boson one will get clear mass separation of the 'other' particle. The requirement of the Z boson in the event will also reduce backgrounds. From Table **??** we see that many of the signals come from h, the 125 GeV Higgs. If we were to look for the h mass we would get overlap between the various final states and it would be difficult to know which final state actually contributed. But by looking for the 'other' particle we can see the clear mass separation. This method is also less restrictive on the analysis since one would not put any explicit selection on the mass of the 'other' particle. In addition, another discriminating variable can be added to combine the Z and the 'other' particle and see if indeed one does reconstruct the hypothesized mass of the originating particle. We can for example restrict the Z($\tau\tau$)other(ll) mass to be within the Higgs mass window to see if it will make the peaks in the other(ll) become clearer.

The SM ZZ* is the only channel that is not a resonance in the other(ll) spectrum. It will have to be fit simultaneously as if it were a separate signal sitting on top of the Drell-Yan background. Using the bump-hunter to pick out this peak is not favorable since it is not a resonant peak and it can overlap with other signal. By studying the shapes in MC and doing a parametric fit to the data one can determine the level of SM contribution to the mass spectrum. In the end when reconstructing the 'other' mass one would see clear bumps for a, Z(dark), h in order of mass. The search can extend to high masses in case some other massive objects happens to appear in association with a Z boson.

1.2.1 Selection and Backgrounds to Z

The selection for this analysis are still to be determined but would require a di-lepton pair if $80 <$m(ll)< 100 GeV for the ee, and $\mu\mu$ channels and would require the use of the Missing Mass calculator for tau mass reconstruction to determine the selection window around the Z mass. In addition a medium/tight selection of the di-leptons will be made for the 'other' particle. When reconstructing the 'other' mass one can parameterize the fit to the background from a control region and extend it the entire range of the mass. At low mass there will be resonant standard model particles which can be modeled with a combination of simulations and the use of the control regions. The backgrounds include Jψ ,Υ, Z, $t\bar{t}$background, and Drell-Yan non-resonant background. In the intermediate mass there will be SM Z+h and ZZ* background as well.

Determine Algorithm for Boosted/Collimated di-tau Pair Identification ; Postdoc Since we are performing a general search where an unknown particle can decay to a Z boson and another potentially unknown particle, some events will have highly boosted and/'or highly collimated di-tau pairs that regular tau reconstruction does not treat. There has been work on ATLAS in this front aimed for reconstructing the channel A $\rightarrow$Z(ll) h($\tau\tau$) [**?**]. In this case the $p_T$of the di-tau system is quite high of an order of 500 GeV. In other cases the $p_T$of the di-tau system can be small but they can be highly collimated. This has been seen in the h $\rightarrow$a($\mu\mu$) a($\tau\tau$) analysis. In fact the algorithm developed for A $\rightarrow$Z(ll) h($\tau\tau$) would not work for this channel because of the large $p_T$cut and the fact that it is seeded by a large R (1.0) Jet. Large R jets only have calibration available for $p_T$larger than 200 GeV. So I propose to develop a high $p_T$di-tau algorithm and a low $p_T$highly collimated algorithm where standard jets of R of 0.4 can be used. A boosted decision tree (BDT) can be developed using the jet substructure information. The variables suggested to be used in the BDT or further studied within a Deep Neural Network are the following:

- core energy fractions, $f_{core}^{sub(lead)} = \frac{\sum_{cells}^{\Delta R=0.1} p_{p,cell}}{\sum_{cells}^{\Delta R=0.2} p_{T,cell}}$
- The subjet energy fractions $f(sub)lead_{subjet} = \frac{{p_T}^{subjet}}{{p_T}^{Jet}}$
- leading track momentum fractions $f(sub)lead_{subjet} = \frac{{p_T}^{leadTrack}}{{p_T}^{subjet}}$
- the maximum track distance Rmax
- the number of tracks n(sub)leading track.

Write General Analysis Suite for xAODs; Postdoc, Akafzade This analysis has leptons including taus in the final states so the analysis suite can be generalized but always adding a constraint of having a Z boson in the final state. Since we would like to perform an inclusive search of any particle decaying to Z+X we will keep this analysis suite very general. However, on top of the general analysis suite one can build tools to make additional requirements on the specific states. For example if there is mass constraint that can be imposed such as the mass of the Higgs.

Determine Background Parameterization from Control Regions, $\mu\mu$ scan ; Postdoc, Akafzade, Hadavand Two control regions (CRs) are used in this analysis to constrain the SM backgrounds in the final fit to the data. The first region, CRj, is used to constrain the low mass SM resonances and Drell-Yan dominated non-resonant background. The second region, CRb, is used to constrain the $t\bar{t}$ non-resonant background. Both regions are defined by first requiring a tagged $\mu\mu$ candidate. CRj is further required to have at least one selected jet and not be b-tagged. CRb is required to have at least two selected jets that have been b-tagged. Any events which are in one of the SRs are excluded from the two CRs.

Determine Background Parameterization from Control Regions, $\tau\tau$ scan ; Postdoc, Akafzade, Hadavand The control region used to determine the parametrization of the jets faking tau objects is defined as having two same sign tau leptons and inverting one of the tau identification criteria. Simulation is used to predict the shape of the contribution from events with two true leptons and hadronically-decaying tau that are either correctly reconstructed or reconstructed from leptons or leptonically-decaying taus. These two parameterizations of the two backgrounds is then used to fit to the data as a more sophisticated template method. The sidebands of the Z boson can be used to validated this approach.

Parameterize Background ; Akafzade, Hadavand As described in section **??** the backgrounds to the multiple BSM analysis will be J/ψ, υ, $t\bar{t}$, Drell-Yan, and Z tails. One can parameterize these background from the control regions described above then fit for the normalization within the signal region similar to what is done in the $\tau\tau\mu\mu$ analysis on ATLAS [**?**]. We also have the SM ZZ* as a non-peaking background which may be difficult to model. This background and the SM resonant backgrounds can be parameterized with MC and used in the fits. I have extensive experience with parameterized fits from the BABAR experiment and can guide my graduate student to model the various SM backgrounds.

Perform two separate scans in Z final state ; Postdoc, Akafzade In the decay of Y $\rightarrow$Z + X we call the mass of X can be reconstructed as X(ee), X($\mu\mu$), and X($\tau\tau$). The three Z scans look at the X(ee),X($\mu\mu$), and X($\tau\tau$) mass spectrum. For the X(ll), l=e,μ spectrum the Z will be reconstructed as Z($\tau\tau$). For the X($\tau\tau$) spectrum the Z will be reconstructed in Z(ll), l=e,μ. The X(ee) and X($\mu\mu$) can be potentially combined if the resolution of the particles are similar enough. The X($\tau\tau$) will not be combined with X(ll) l=e,mu since the resolution is quite different and the bump-hunter would not gain in looking for two overlapping bumps of vastly differing resolutions. The use of the bump-hunter will allow for a first statistical pass at the data to determine if there is an existence of signal in the samples.

Develop and Optimize Bump-hunter to Scan Data ; Hadavand, Akafzade I have previously worked on a bump-hunter which would be independent of the signal model used. I called this program Signal Parameter Independent Fit (SPIF). Using the parametrization described above we fit the data and remove a window where signal is expected. The background is then extrapolated within this window and the difference of the number of events in the window versus the fit extrapolation is determined. A p-value is determined using Poisson statistics for the difference between the number of events in the window and the extrapolated background within the window. A scan is done using as input the step size and a of range of window sizes. Several scans are performed changing the window size and step size iteratively until the p-value no longer improves within a specified precision. Once all iterations are performed, the window(s) with the smallest p-value(s) is(are) reported. If the bump-hunter analysis reports no significant signal then a coarser binning can be used for the limit setting saving time and CPU power.

Develop Limit setting software for various final states ; Akafzade, Postdoc Once the background is parameterized and the normalization is determined from the signal region, we can determine limits using a binned maximum likelihood fit using HistFactory as is usually done on ATLAS. For a search in a large window of mass typically a fine grid of masses are tested. However with the input from the SPIF program we can only use a fine grid in regions where the p0 value is low indicating some deviation from the background. This will save CPU time in setting the final limits. Since our search includes several final states, these final states must be statically combined for each channel to get the best limits.

1.3 Higgs Decays to Invisible Particles (PI: White)

A key question for the Higgs boson is whether it couples to the dark matter. If dark matter is indeed composed of particles, then presumably the 125 GeV Higgs, or some other Higgs boson, is at least partially responsible for their mass generation (assuming that the new particles have a weak interaction). We will continue to explore this possible connection by searching for evidence of Higgs decays to invisible particle(s). Limits on the decay of the Higgs to invisible particles from the LHC experiments can be used in turn to set limits on the process of dark matter particle-nucleon scattering, which are highly competitive with those from direct searches. The spin-independent cross-section for dark matter scattering on nucleons via Higgs exchange is directly related to the invisible width of the Higgs.

The most promising channel for this analysis is Higgs production through Vector-Boson Fusion (VBF) as shown in Figure **??** (left). The signature for this process, with an invisible Higgs decay, is two forward jets, widely separated in pseudorapidity, and large missing transverse energy. There is also a smaller signal contribution from gluon-fusion plus two jets. The two main backgrounds are $Z(\to \nu\nu)$ +jets and $W(\to \ell\nu)$ +jets (including τ decays), where the charged-lepton in the final state is not identified in the detector. There are also small backgrounds from the strong production of jets (multijet), $t\bar{t}$, and diboson production. For the Run 1 analysis White served as contact editor together with Ketevi Assamagan(BNL), and Bill Quayle(LBNL). 20.3 fb-1 of data at 8 TeV were analyzed and a limit of 28% was set on the branching ratio of the H(125) to invisible particles at 95% confidence level (with an expected limit of 31%) [**?**]. This was the best limit set by all ATLAS and CMS analyses for Run 1. The use of a $W(\to \ell\nu)$ control region, as well as the $Z(\to \ell\ell)$ control region, to estimate the $Z(\to \nu\nu)$ +jets background was a significant factor in setting our low Run 1 limit. Figure **??** (right) also shows the limit, as a function of mass, that our analysis sets on the Higgs-nucleon cross-section, and the comparison with direct search limits. White presented the ATLAS and CMS results on invisible decays of the Higgs at the LHCP2015 Conference in St. Petersburg, Russia. [**?**]

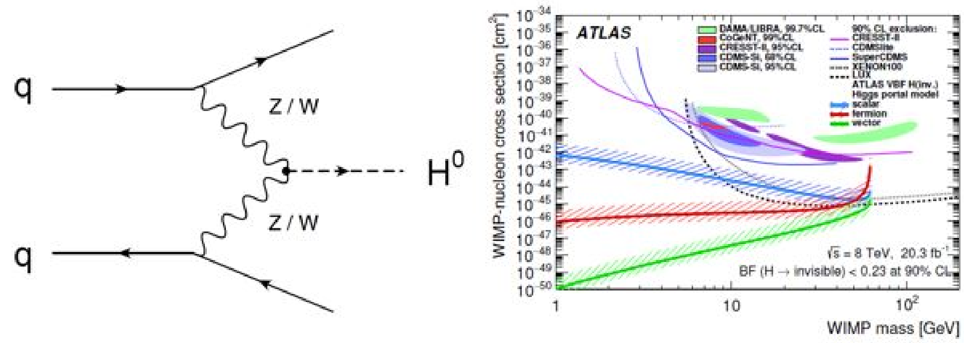


Figure 2: (left) Higgs production via Vector-Boson Fusion. (right) WIMP nucleon cross section as a function of the WIMP mass.

The increased Higgs production cross-section at 13 TeV, and the higher integrated luminosity from Run 2 will allow us to probe this process with significantly increased sensitivity over our Run 1 results. White (working with Alex Madsen (DESY)) is analysis contact for the Run 2 Higgs to Invisible analysis. Weekly meetings are held to coordinate the contributions to the analysis: data/Monte Carlo samples and comparisons, trigger(s), control regions specification, theory uncertainties, and limit setting. We have also been holding workshops at critical times to advance the analysis. Given the rate at which ATLAS is acquiring integrated luminosity, we expect in 2016 to reach the point at which we begin to be limited by systematic errors rather than statistically limited. In this respect investigations are ongoing into potential methods for cancellation of systematics in efficiency ratios versus the usual application of transfer factors from control to signal regions. Specific contributions from UTA to the Run 2 analysis include calculating the electroweak corrections to the the VBF Higgs signal, and providing the parton distribution function (pdf) uncertainties on the signal. For the electroweak corrections, we have set up HAWK [**?**] on the UTA Tier 3 in multi-threaded mode as more than 10^9 events are needed to achieve sufficiently precise corrections. HAWK provides the calculation of differential EW correction factors, which can be used as differential EW reweighting factors to improve QCD-based predictions. The results of the HAWK calculations are shown in Figure **??** - the reweighting factors have essentially a linear dependence on the Higgs Pt, and a linear fit yields the required electroweak correction.

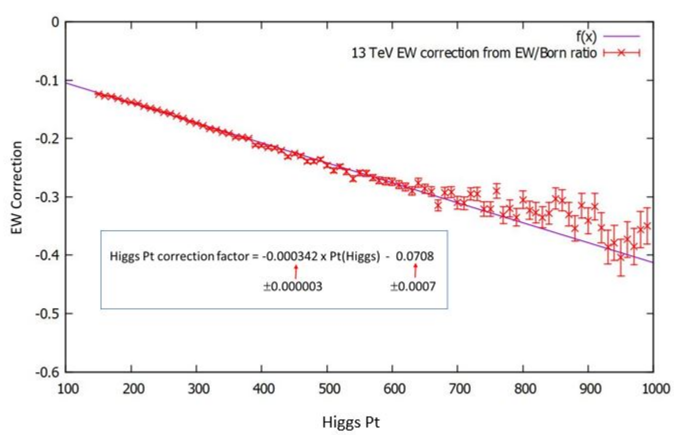


Figure 3: Electroweak corrections to the Higgs pT distribution in the VBF selection.

For the calculation of the VBF signal pdf uncertainties, UTA has been running the generator Powheg v.2 [?] which allows the storage of multiple weights for each event. Our original VBF signal dataset was created using the CT10 pdf set. There are now recommended pdf sets for LHC Run 2 which combine CT14, MMHT2014, and NNPDF3.0 [?]. Currently, after exchanges with Higgs and Exotics group colleagues we have chosen to use the PDF4LHC15-nlo-30-pdfas set. This is a Hessian set that allows straightforward calculation of the uncertainties, which is the variation in the number of weighted events passing the VBF selection. This work is being carried out by UTA Honors undergraduate student Darshan Chalise under White's direction. UTA will continue to provide both the electroweak and pdf uncertainties for future versions of our analysis.

The current analysis plan is to write a paper based on the 2015-16 data set, estimated to comprise about 30 fb^{-1}. The goal is to have this result ready for Moriond 2017. White will take on a new graduate student in the Fall 2016 semester. This student will work on the 2017-18 extension of the VBF Higgs to Invisible analysis. Going forward we will focus on improvements and changes to the analysis that will be necessitated by the rising instantaneous luminosity - pileup mitigation, particularly for forward jets, and reduction of the systematics for the jet energy scale and resolution. Work in these areas will form part of White's new student's ATLAS qualification tasks. Of significant physics interest, with reducing limits on the Higgs to invisible branching ratio, will be our ability to exclude models that predict an enhanced value of this ratio. There is a natural evolution of White's physics interest in this topic also with the ILC project (see the ILC section below), which will allow much stronger constraints to be set on Higgs to invisible decays.

VBF HIggs to Invisible Analysis Timetable of Activities

2017

- New UTA graduate student starts work on ATLAS
- Publish Run 2 paper based on 2015-16 dataset
- Work on "interpretation" paper for Run 2 results, DM-nucleon limits and more
- Study strategies for reduction of jet systematics
- Update Higgs to Invisible limit as more data becomes available

2018

- Graduate student pursues ATLAS qualification with work on strategies for reduction of jet systematics
- Contribute data/MC comparisons and cutflow checks
- Provide updated electroweak signal corrections, and pdf uncertainties
- Graduate student begins year at CERN
- Work on branching ratio limit from full Run 2 dataset

2019

- Publish full Run 2 result
- Work on analysis strategies beyond Run 2

1.4 SUSY Physics (PI: De, Farbin)

Despite no evidence of Supersymmetry (SUSY) in LHC Run 1 and first Run 2 data, this extension of the Standard Model's symmetries continues to remain the most compelling mechanism to avoid the fine-tuning problem of the electroweak symmetry breaking mechanism (also referred as the hierarchy or naturalness problem), while also providing Gauge Unification and a Dark Candidate. The current highly successful LHC run, with a significant increased center of mass energy and integrated luminosity, provides a brief window where data-doubling time is short and large strides can be made in the search for new particles. As LHC nears end of Run 2, further strides will require more sensitive techniques that can target difficult regions while also search broadly for excesses.

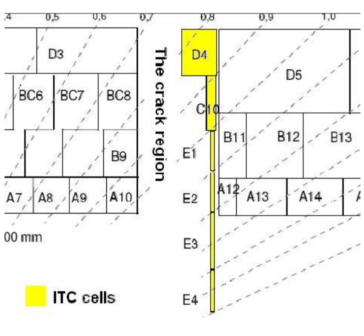
This section overviews activities and plans of UTA SUSY group, consisting of faculty De and Farbin, postdocs Usai and Heelan, and students Bullock, Little, and Rogers.

1.4.1 Squarks and Gluino (PI: Farbin)

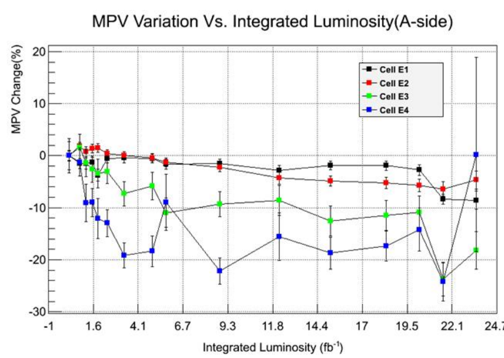
Service at ATLAS

2 Intermediate Tile Calorimeter (PI: De, White)

The Intermediate Tile Calorimeter (ITC) was designed to fill the gaps between the central barrel calorimeter and the extended barrel calorimeters, and was built at UTA. Figure **??** shows a schematic view of part of the ATLAS calorimeter, showing the components of the ITC. For particles which originate at the nominal interaction point, the ITC extends over approximately $0.8 < |\eta| < 1.6$. The region $0.8 < |\eta| < 0.9$ contains 311 mm thick steel-scintillator stacks, similar in design to standard Tile Calorimeter submodules. Between $0.9 < |\eta| < 1.0$, the stacks are 96 mm in the z-direction. The combined $0.8 < |\eta| < 1.0$ region of the ITC is called the plug. In combination with the support structure for the scintillators, it is called the ITC submodule. For the forward region, the active elements of the ITC consist of scintillator only due to space constraints. The scintillators between $1.0 < |\eta| < 1.2$ are called the gap scintillators, while those between $1.2 < |\eta| < 1.6$ are called cryostat scintillators. Some additional scintillators, designated E4-prime were installed in 2015, covering $1.6 < |\eta| < 1.72$ and a small sector in ϕ, in order to explore the possibility of extending ITC coverage for improved electron and jet measurements. Together, all these ITC detectors improve the measurement of total energy in the intermediate region, thereby improving the jet and $\not{E}_T$ resolution of ATLAS.



(a)



(b)

Figure 4: Left - Layout of the Intermediate Tile Calorimeter. Right - Average change for ITC E-modules vs. integrated luminosity.

It is anticipated that the E cell scintillators will need to be replaced in the long shutdown in 2019, due to the expected high levels of radiation damage. White, with postdoctoral associate Park, previously carried out studies of radiation damage using Gaussian plus Landau fits to the signal distributions for all E-cell channels. This proved to be a very challenging exercise due to the high degree of variabilty of the signal profiles. Nevertheless, results were obtained as shown in Figure **??**. Most of the decrease in response can be atributed to the downward response of the PMT's due to continual exposure to light during the run, as shown by the laser illumination of the photocathodes. However, there was a few percent decrease on top of this effect that was attributed to radiation damage. This approach to monitoring decreased response has now been replaced with the use of minimum bias data plus the laser measurements. The replacement of the E-cells scintillator affords the opportunity to revisit the η and ϕ segmentation of the cells. In order to determine the best layout for optimization of energy resolution in this region, UTA has been working with the Tiblisi group to examine the distributions of jet energy fractions in the E-cells and the improvement in energy resolution achievable by the optimal use of the individual E-cell signals. The work at UTA has been carried out by Honors undergraduate student Niyusha Davachi under White's supervision. As an example, Figure **??** shows the fractional energy contribution for each of the E-cells, for QCD jet events where the jet axis lies in E4, for three groupings of adjacent ϕ cells (3,5, and 7). By studying these fractional energies for jets within all the E cell η ranges, we will optimize both the use of the deposited energies for jet reconstruction, and the propose potential new layout(s) for the E cells. This work is ongoing with the goal of providing a recommended layout of the new E-cells scintillator in late 2017/18, when the new tiles will have to be ordered.

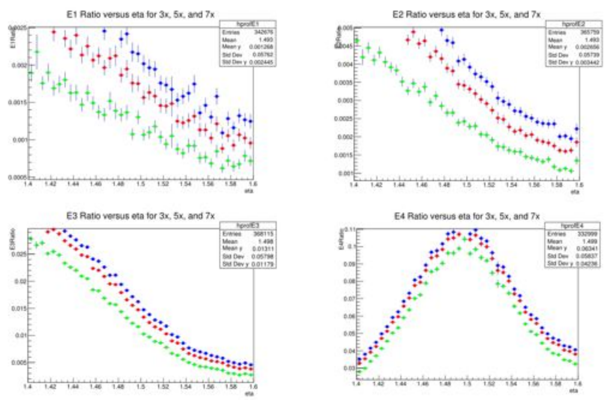


Figure 5: Fractional contribution to jet energy by the Ei (i = 1,2,3,4) cells for the case where the jet axis lies in the E4 range, $1.4 < |\eta| < 1.6$.

While the scintillator replacement is not within the scope of US ATLAS work for Phase I, the UTA group has made contributions to the estimation of the expected integrated radiation dose during Run 2, to the specification and identification of radiation-hard scintillator, and will be involved in the procurement, installation and testing of the new tiles. This work will also be included in the qualification tasks for White's new graduate student.

ATLAS Tile Calorimeter Timetable of Activities Our work on the Tile Calorimeter/ITC will be carried out in collaboration with colleagues in CERN and Tblisi.

2017

- Complete the study of the optimal use of exisiting E cells for improving jet energy resolution
- Update expected radiation doeses for E cells based on known and projected Run 2 luminosities.
- Study/propose alternative E cells configurations for the 2019 tile replacements
- Continue as a member of the Tile Calorimeter Speakers' Committee.
- Contribute DQ Validator shifts

2018

- Complete plans for ATLAS ITC Tile/Fiber replacements in LS2.
- Investigate the availablity of radiation-hard scintillator for new ITC tiles.
- Prepare (with ATLAS Tile Institutes) tile/fiber assemblies for installation in LS2.

- Graduate student begins time at CERN, with Tile Calorimeter qualification tasks.
- Contribute DQ Validator shifts
  2019
- Study effects of radiation on light yield/transmission for dismounted ITC tiles.
- Contribute effort to installation and testing of the new ATLAS ITC E-cells.
- Graduate student returns to UTA.

3 Trigger (PI:)

Computing at ATLAS

Computing costs for HL-LHC are estimated to be at least a factor of 5 more that current LHC [], and likely much more due to the stalling of Moore's Law. While greater use of HPCs in HEP will ideally alleviate some of the problem, HEP software has yet to harness the parallelism in the processors, like GPUs, where these systems get most of their horsepower. Farbin's success in Deep Learning has its roots in his projects with undergrads on GPUs and the GPU systems they build and share with XX colleagues and collaborators. [The primary machine (2x 12-core Xeon, 128 GB RAM, 50 TB disk) hosts one previous generation and three older NVidia GPUs.] Farbin's initial work with these GPUs was aimed at understanding how to efficiently use them in the ATLAS software framework resulting in 4 unfunded NSF collaborative proposals. Section **??** describes how Farbin will direct this thrust of work towards migration of ATLAS trigger to multi-thread version of Athena and integration of GPUs.

Meanwhile, the world is in the midst of a renaissance in Machine Learning and Artificial Intelligence, known as Deep Learning, driven by the emergence of large data sets, powerful Graphical Processing Units (GPUs) processors, and new techniques to train billion-neutron multi-layer artificial neural networks. Systems trained on raw and sometimes unlabeled data, can now recognize objects, detect human emotion and intent, play video games, translate between languages, generate mathematical proofs, sometimes better than humans and most importantly with minimal engineering. Developed in University Machine Learning labs, DL has led Google, Facebook, and other industry-leading companies to rethink everything, building Artificial Intelligence teams, software, processors, and cloud services, and demonstrating impressive feats. DL is the first multi-domain application that requires and easily harnesses the power of specialized processors, like GPUs, and supercomputers (i.e. HPCs). Section **??** describes Farbin's efforts to apply DL to HEP.

4 Core Trigger Software (PI: Farbin)

5 Deep Learning (PI: Farbin)

Space constraints prohibit pedagogical discussion of Deep Learning and details of much of the activity described and planned out in this section. Surveys of DL activity in HEP and much of these details can be found in Farbin's recent talks [], for example at HEP Software Foundation [] HSF, ATLAS Machine Learning workshop [], or the Harvard Big Data Conference []. This section is organized into DL thrusts that sometimes span multiple experiments: Simple Classification, Matrix Element Acceleration, Imaging Detector Reconstruction, and Tracking.

Simple Classification with Deep Learning The first application of DL in HEP demonstrated that (fully-connected) DNNs out-perform shallow networks and derive new "features" from 4-vectors beyond traditional observable. Farbin recently demonstrated this simple application of DNNs with help of Chris Rogan (Harvard) and Paul Jackson (Adelaide). They showed that 4-vector based DNNs out-performed a Jigsaw-based DNNs in correctly distinguishing between different SUSY-like decay topologies. This work is in a step in an effort to build a DNN that generically classifies events and enables unsupervised general searches for new phenomena. They are also now applying DNNs to compressed-SUSY scenarios, building on experience of the ICHEP 2016 Jig-saw result and following Rogan and Jackson's recent paper []. Section **??** provides additional details on these topics in the context of SUSY. [Hadavand and Brandt will apply similar techniques to their work...]

Signal and background classification tasks are the first and simplest and can be easily enhanced by replacing traditional classifiers with DNNs. Groups in ATLAS are applying this idea to tasks like b-jet or boost-object tagging. Farbin has developed a Deep Learning Tutorial covering a variety of DNN tasks, such as event or object classification with any dataset. The tutorial introduces a thin framework (DLKit) developed by Farbin that simplifies running large-scale DL studies using Keras, a powerful python-based DL framework which supports both Theano and TensorFlow backends. Postdoc Heelan, who manages the ATLAS software tutorials and workbook, will introduce the DL tutorial at the October 3rd session, with subsequent iterations adding all of the additional tasks Farbin is currently performing in DLKit, such as Matrix Element Regression and 2D and 3D Imaging detector classification and Energy regression. Farbin, Brandt, Hadavand, Asaadi, and Jones have committed students to applying DNNs to various problems, and this DLKit and tutorials are integral to these projects.

While the tutorial helps address one obstacle to broad adoption of DL, namely familiarity and full end-to-end working examples, access to GPUs, which give two orders of magnitude acceleration of DL training with respect to CPUs, remain as the next biggest obstacle. For the past few years, Farbin has granted access to the GPU system he as built with his undergrads to XX HEP scientists from YY experiments (LArIAT, DUNE, MicroBooNE, NEXT, CMS, ATLAS). Farbin performed an early study of turning regression problems into classification problems on the Oakridge's Titan HPC via PANDA WMS with the help of Sergey Panitkin (BNL), the first use of Titan's GPUs in HEP. A subsequent iteration of of the DLKit tutorial will include submission of Hyperparameter scan DL jobs to Oakridge's Titan computer and ideally any other HPC accessible via PANDA and with suitable software.

Matrix Element Acceleration with Deep Learning The Universality Theorem [] states that a sufficiently large Neural Network can represent an arbitrary function of any input dimensions. The theorem implies that fast DNNs can potential encapsulate prohibitively expensive computations, for example Matrix Elements in context of NLO and NNLO computations, which are becoming increasingly important for the LHC, or the application of Matrix Element Method (MEM), which is in principle the most powerful search technique but is sparsely applied due to technical complexity and computational demands. The idea is to perform the computations once using significant computing resources, for example an HPC, and train a DNN to efficiently (in both memory and speed) accurately reproduce the same computation for subsequent event generation, integration for cross-sections, or application of MEM.

Farbin has been pursuing both of these problems in collaboration with Tancredi Carli (CERN), ATLAS's next Deputy Physics Coordinator and Tobias Golling's group (U. Geneva). Carli has produced a one billion event sample of NLO $t\bar{t}$ in Sherpa which he has been studying on Farbin's GPU system due to memory requirements. He has been attempting to encapsulate event weights in a high dimensional (i.e. incoming and outgoing 4-vectors) adaptive binning histogram using the foam [] method. Simultaneously Farbin has developed a Matrix Element DNN (MEDNN) to achieve the same task. Since Golling's group, who initially relied on Farbin's GPU system, is pursuing a similar task for Matrix Element Method based analysis, Farbin joins Golling's group meetings and shares ideas and code. DNN training for such a regression task is essentially a high dimensional fit, which due to the non-linearity of NNs, is often biased unless a proper cost function is applied. This problem is discussed in the Imaging Detector Energy Regression description below. For MEDNN, the state-of-the-art turns the regression (i.e. fitting) into a classification problem by binning the target with bin learned bin edges.

Imaging Detector Reconstruction with Deep Learning Starting in 2014 Deep Convolution Neural Networks (CNNs) have exponentially improved performance on ImageNet, a one-million image classification challenge [], to now super-human performance []. An obvious application of CNNs is the classification tasks, such as particle identification, in "imaging" detectors such as Time-Projection Chambers (TPCs), Cherenkov Imaging detectors, and high granularity calorimeters. The application in HEP of this idea was in the Nova collaboration, where they were able to obtain 40% better electron efficiency for same background rate as their best techniques [].

LArTPC In fall of 2015, Farbin CNN-based demonstrated particle identification in LArTPC with simulation of the LArIAT Experiment []. Despite a great deal of multi-experiment (e.g. ArgoNeuT, LArIAT, MicroBooNE, DUNE, ...) effort, event reconstruction in LArTPC has proven be challenging, with performance still far from expectation and poor neutrino reconstruction. Farbin's Inception [] based CNN treated raw data from the TPC as imagines, and was able to achieve significantly better performance than traditional reconstruction in both particle and neutrino reconstruction [] (give example numbers?)). This effort has now evolved to a collaboration with computer scientists Pierre Baldi and Peter Sadowski at UCI. While the ultimate goal is demonstrate end-to-end DL-based Neutrino reconstruction, the first goal is to design optimized networks for particle and neutrino classification and energy regression. The first step was to produce large samples of simulated events with flat energy spectrum. Using Farbin's local machines Shahsavarani and undergrad Hilliard have so far produced 15 million events of every particle species, which is a largest LArTPC sample ever produced (?). This dataset is public, is intended to facilitate collaborations, and is already being used by independently by HEP and DL researchers.

The collaboration with UCI has yielded several particle and neutrino classification and regression networks, including Siamese [] Inception and ResNet [] based networks that seem to require less depth for LArTPC tasks than image classification. Obtaining better classification performance than automatic reconstruction has proven to be rather easy. Recently MicroBooNE presented some promising first studies [], based on work that was initiated on Farbin's GPU system. Farbin et al we able to obtain better performance, training for a week with $O(100k)$ down-sampled raw events, for example achieving 2% fake rate at 80% for electron versus neutral pion discrimination, a critical benchmark for separation of charged current from neutral current neutrino interactions. However obtaining the design performance (1% fake rate) will likely require full resolution and deeper networks train for long time on the significantly larger training sample Farbin et al have produced.

Obtaining good energy reconstruction has proven to be difficult. In order to avoid bias, Farbin et al employ likelihood based cost functions that also provide a per-event resolution estimate. First studies with small networks on down-sampled data obtain poor electron resolution with 11% sampling term, significantly worse than the expected 3%. Meanwhile Muon energy reconstruction relies on measuring multiple scattering angle, and thereby requires full detector resolution. Again, these studies are at the stage of much more challenging training requirements and are underway, with the goal of paper submission by end of 2016.

Farbin and Asaadi propose to implement the network architectures and techniques developed in these studies as DNN-based algorithms in the software framework common to nearly all LArTPC experiments, LArSoft []. This work will be carried out primarily by Shahsavarani and undergrad [Asaadi insert name here] in collaboration with Robert Sulej (CERN, Fermilab, ...), who has been pursuing DNN-based electromagnetic versus hadronic hit identification, also on Farbin's GPU system. As these algorithms are implemented, they can be tested or trained on LArIAT data. The goal will be to provide full end-to-end DNN-based neutrino reconstruction in LArSoft by the end of 2017.

Gas TPC The neutrinoless double beta ($0\nu\beta\beta$) experiment NEXT, relies on high pressure xenon (HPXe) Gas TPC, read out by SiPMs to produce 3-D images of beta decays. NEXT relies on topological signatures to separate signal events (two electrons) from background events (mainly due to single electrons with kinetic energy comparable to the end-point of the $0\nu\beta\beta$ decay). Late 2015, Farbin, with the assistance of Josh Renner (?), ... (?), demonstrated that CNNs can nearly perfectly separate this signal and background in an idealized toy simulation. Since then, they have shown CNNs out perform the traditional technique in full simulation. They also used 2D DNNs to easy compare different detector granularities and understand the relative contribution of physics processes to the fake-rate. This activity is detailed in a paper (with Farbin as co-author along with the NEXT collaboration) that is nearly ready for submission. Jones is committing undergrad XXX and graduate student XXX, to upgrade the technique to 3D and attempt to identify the decay point and angle, in an effort to test Lorentz invariance [Ben, do I put this in?].

Calorimeters The ATLAS Electromagnetic and Hadronic calorimeters produce 3D images in of variable granularity in η, ϕ versus depth (i.e. the LAr presampler to the Tile D layers) of energy deposits. Particles, such as photons, are identified by their characteristic shower profiles, with their energies determined via a weighted fit of layer-wise deposits calibrated to test beam and Z decays. Any improvement, for example in photon identification or energy resolution, can dramatically improve searches and measurements, for example producing narrower Higgs peaks with less background. This calorimeter (as opposed to CMS's crystal EM calorimeter) is ideally suited for application of CNN for classification and energy regression. Indeed several factors give hope that significant improvements can be achieved. For example, energy reconstruction in the LAr EM calorimeter currently does not use shower shape information and is not correcting for variations in the LAr calorimeter's characteristic accordion structure. Similarly the hadronic calibration does not use sampling information.

The variable granularity of the ATLAS calorimeter can likely be built into the CNN architectures. Since simulation does not faithfully reproduce the shower shapes, simulation trained CNNs can be initially calibrated on $Z \rightarrow ee$ or testbeam data. While training on data is also possible, for example training on data Z decays using likelihood-based cost functions that account for Z line-shape and calorimeter resolution, an interesting direction is hybrid training with adversarial networks. An example of this technique simultaneously trains the classification or regression network with and an adversarial network learning to distinguish data and simulation. The full network is then trained until data and simulation cannot be distinguished.

Another potentially high impact of DNNs to calorimetry is fast showering. Full Geant4 shower simulation in the ATLAS calorimeter takes of order of an hour. Fast shower techniques such as shower libraries or high dimensional binning of shower observable generally suffer from intractable memory requirements. Zach Marshall et al (Berkeley) have more efficiently stored shower observables in shallow neural networks. DNNs may provide a much more powerful technique. Starting with examples only, Generative DNNs have been demonstrated to generate new images of faces or hotel rooms, or text in style of the example author (e.g. Shakespeare). Two techniques are likely relevant to calorimetry. The first is Generative Adversarial Networks, which starting from random input trains a network that simultaneously produces the desired output and attempts to distinguish generated from real examples. The network is trained when it no longer can make the distinction. Variational Autoencoders train a 2 part network: one that "encodes" real examples into a latent lower dimensional representation of Gaussian distributed variables, and another that "decodes" to an image trained to reproduce the original. Once trained, the decoder can be primed to then generate new examples.

A significant obstacle to applying CNNs to the ATLAS calorimeter is accessibility to data. The energy deposits into the 200k cells require significant storage and are only retained in the difficult to access Event Summary Data (ESD). With a baseline of ≈ 1 in 10^4 jet rejection, CNN training will require large samples of specially filtered EM-like jet backgrounds, finely binned to compensate for drop in jet-cross section. Finally, due to ATLAS's strict data-sharing policies, collaboration with DL experts is difficult. Farbin and graduate student Leslie Rogers are working to address these issues and assemble appropriate ATLAS training sets,

In meantime, Farbin has been collaborating with CMS colleagues Maurizio Pierini (CERN) and Jean-Roch Vlimant (CalTech) to generate simpler public datasets where application of DNNs to calorimetry can be explored in collaboration with DL experts and without unnecessary complications. Starting with the high granularity LCD CLIC calorimeter concept, they have so far simulated 2 million photon and neutral pions and presented first classification studies were presented in July 2016 []. With the goal a paper by the end of 2016, Farbin is currently applying the energy regression techniques developed in LArTPC to this dataset.

Ideally, the very clean environment of the LArTPC and Gas TPC and this simple LCD dataset, can serve as a stepping stone for developing the classification, regression, and generation techniques described in this section to the ATLAS calorimeter and the pile-up ridden LHC environment. Exploring and implementing these techniques in ATLAS will be a part of Rogers' PhD thesis, building on Farbin's ATLAS software and DL experience and Heelan's extensive background with the calorimeter (e.g. she is the editor of the Tile performance paper) and test beam. The goal is to first tackle photon identification and then photon/electron calibration. Of critical importance will be handling of pile-up. If successful, the technique will be implemented in ATLAS's framework for further study and use by other collaborators. Extension of the technique to EM/hadronic cluster identification and calibration should be straightforward next step. Postdoc Griffiths, who contributes significantly to τ identification, will investigate CNN applications to τs. Simultaneously these efforts will explore applying the generative DNN fast showering technique developed in the context of LCD, to ATLAS.

HEP is confronted with two fundamental problems in the current generation of HEP experimental software: the inability to take advantage and adapt to the rapidly evolving processor landscape, and the difficulty in developing and maintaining increasingly complex software and computing systems by physicists. DL and DL software systems provide a paradigm-shifting solution to these problems. It may be possible to replace the millions lines of code, meticulously crafted by thousands of physicists, with large neural networks that are simply trained on raw simulated data. Not only are these networks much simpler and faster to compute than traditional HEP algorithms, they inherently make efficient use new processors. These systems can provide scalable implementations of existing HEP algorithms.

Tracking Pattern recognition rate in particle tracking scales quadratically with hits in the tracking detector. As a result, tracking in 200 pile-up HL-LHC events is one of biggest challenges for the HL-LHC, where some tracking and vertex finding at 40 MHz bunch-crossing might be required for the trigger. While some are investigating dedicated hardware, such as GPUs, FPGAs, or associated memory, a group of ATLAS and CMS physicists, including Farbin, are hoping that by presenting the HL-LHC tracking problem as a Machine Learning challenge (TrackingML) with a prize, solutions arise that scales better with number of hits []. One source of inspiration is DeepMind's AlphaGo [] artificial intelligence agent, which was able to assess moves by looking at the whole board with a DNN instead of performing a look-ahead tree search. This DNN was trained through human expert and self-play games.

Preparing this challenge requires generating HL-LHC like events in an appropriate detector, providing baseline traditional tracking software for comparisons, and developing mechanisms to benchmark and assess the performance of submitted algorithms. The majority of the work so far has been carried out by Andreas Sulzberger (CERN), who is currently in charge of ATLAS reconstruction and formerly a tracking expert. He has developed a standalone simulation and tracking framework, known as ATLAS Common Tracking Software (ACTS). Farbin's contribution to the project so far has been data conversion to more ML friendly HDF5 format. Farbin and undergrad Hilliard are assuming the responsibility of developing the automatic benchmarking mechanisms, likely using Docker containers on hardware Farbin will dedicate to the project.

Upgrade at ATLAS

6 Tile HL-LHC Upgrade (PI: De, White)

7 Tile Low Voltage Power Supply(LVPS) Upgrade (PI: Brandt, Hadavand)

8 High Luminosity-LHC Tile Upgrade Projects

In preparation for High Luminosity LHC (HL-LHC), various upgrades of the ATLAS detector to cope with the new conditions are being planned. One of these projects, involving the replacement of the 2048 low voltage power supplies (LVPS) required for operation of the ATLAS Tile hadronic calorimeter, became available last year. Building on UTA's connections in the TileCal since its inception, Hadavand and Brandt assembled a group and proposed that UTA take over this project. Our proposal was well-received, consequently, Hadavand is now the L3, or deliverable manager, of this project for the ATLAS detector while Brandt is the institute contact. The construction phase of this 6-year 1 million dollar project is expected to be covered by an NSF MREFC proposal in progress.

Starting in 2023 the LHC will be shutdown for 2.5 years in preparation for HL-LHC upgrade to achieve 5.0 $\times 10^{34}/cm^2s$. Hadavand and Brandt have assumed the responsibility for the testing and production of half of the entire 2048 low voltage power supplies (LVPS) needed for HL-LHC running, a project that will cost about 1 million dollars over the next few years, the bulk of which is anticipated to be provided by an NSF MREFC grant. Hadavand is the deliverables manager or CAM for the low voltage power supplies overseeing the work of UT Arlington as well as that of Northern Illinois University which is responsible for integrating the UTA power supplies into boxes that will go into the detector. The UT Arlington group also has responsibilities on the Tile Pre-processor for HL-LHC. We currently share an electrical associate (EA), Seyedali Moeyadi, on these two projects.

The EA has worked closely with our research faculty Guilio Usai at CERN and has been involved in the June TileCal test beam. We have also procured funding from the university for an electrical engineering (EE) PhD student, Michael Hibbard, whose thesis will be based on this project.

We are currently in a transition phase assuming responsibility for the project as Argonne National Labs, who designed and built previous versions of power supplies is assuming responsibilities in the upgraded tracking detector. They have produced a working prototype, but the final design of the power supplies including interface changes to account for other system upgrades is scheduled for 2018, and will be our responsibility. A timeline of the project is as follows (more details are shown in table **??**): During 2017 the research and development component of the project will be in the design of the elevated temperature testing apparatus (Burn-in Station) for the power supplies. Such a system is necessary to age the components and identify power supplies with early mortality rates. A temperature analysis of the system has also been performed to determine whether the cooling capabilities of the system are sufficient for running the power supplies in redundant mode, where the current is twice the nominal. This is a fallback mode in case of a power supply failure, the other supply in the drawer can provide power to the full drawer. After determining changes needed from components interfacing to the LVPS such as the ELMB++ a small number of prototype LVPS will be made in 2019 with the new design. These LVPS will be assembled into boxes by NIU and sent to CERN for testing in the vertical slice test. From 2019-2022 we will be producing LVPS in batches testing and burning them in for quality control. This is a huge undertaking and will require a detailed and well-documented plan that a set of undergraduate students will follow for testing the LVPS.

Perform Model Dependent Exclusions ; Postdoc With the use of the branching fractions for each model exclusions on various model parameters can be made using the cross section limits. For NMMSM or 2HDM the exclusions will be in the $\tan\beta$ vs mA plane and $\tan\beta$ vs $\cos(\beta-\alpha)$ plane.

8.0.2 Tile HL-LHC LVPS Upgrade

The preliminary schedule and tasks for the Tile HL-LHC LVPS upgrade project is shown in table **??**.

9 International Linear Collider Project (PI: White)

The study of the Higgs sector continues to be a major part of the HEP physics program, and will continue to be for the next 10 - 20 years. The full exploration of this sector will require the combination of the upgraded, high luminosity LHC plus precision results from a lepton collider. The lepton collider that is closest to being realized is the International Linear Collider in Japan. UTA has been engaged, since 2002, in studies for the SiD Detector Concept for the ILC. This work has been an investment in the future of HEP for our group, and is consistent with our approach of having an involvement in each generation of colliders. The SiD Detector Concept was one of two designs validated by the International Detector Advisory Group. Since 2012, White has served as co-Spokesperson for SiD, with co-Spokesperson Marcel Stanitzki(DESY). The SiD design study achieved an important milestone with the production of the Detailed Baseline Design (DBD) [**?**] together with the TDR for the ILC Accelerator. The DBD is a compreshensive statement of an advanced detector design (see Figure **??** (left)) [**?**] that will enable the study of a full range of TeV scale physics. This includes precision Higgs measurements, a detailed study of top physics, which is closely connected to the phenomenon of electroweak symmetry breaking, and a sensitive

Task	Personnel	Start Date	End Date
New Burn-in Station Design and Fabrication	Hibbard, EA, EE	01/30/17	12/15/17
Prototype	-	01/29/18	08/30/19
Procurement of brick components for prototype V8.2 bricks	Hibbard, EA	01/29/18	05/11/18
Basic Check-out and burn-in (Prototype)	Hibbard, EA	04/22/19	05/24/19
Prototype Review	EE, EA	05/27/19	08/30/19
Integration and testing of vertical slice	Hibbard, EA	06/03/19	07/26/19
Finalize V8.3 pre-production design	EA, EE	07/29/19	08/23/19
LVPS pre-production design review	EA, EE	08/26/19	08/30/19
Pre-production	-	09/2/19	12/30/20
Check-out and burn-in tests on pre-production bricks	EA, undergrads	07/06/20	09/25/20
Ship bricks to CERN	EA	09/28/20	10/02/20
Integration tests at CERN and final review	EA	10/05/20	12/31/20
Production	-	01/04/21	04/08/22
Production PCB Assembly	EE,EA	04/12/21	06/04/21
Check-out and burn-in (16 to start and find any issues)	undergrads	04/19/21	04/30/21
Check-out and burn-in (64 to confirm production)	undergrads	05/03/21	05/28/21
Check-out and burn-in (1000)	undergrads	05/31/21	04/08/22

Table 4: The HL-LHC Tile LVPS upgrade schedule.

probe of new physics, such as that from additional gauge bosons and extra dimensions at high mass scales, in a program that is complimentary to that at the LHC. The reach of the ILC in precision measurements of Higgs couplings is shown in Figure **??** (right). The branching ratio for Higgs to invisible decays can be probed at the 1/2% level at the ILC. This is the level at which theoretical studies (Ref. xx) show that significant effects from new physics can be expected. The ILC is thus a discovery machine both through direct searches and precision measurements.

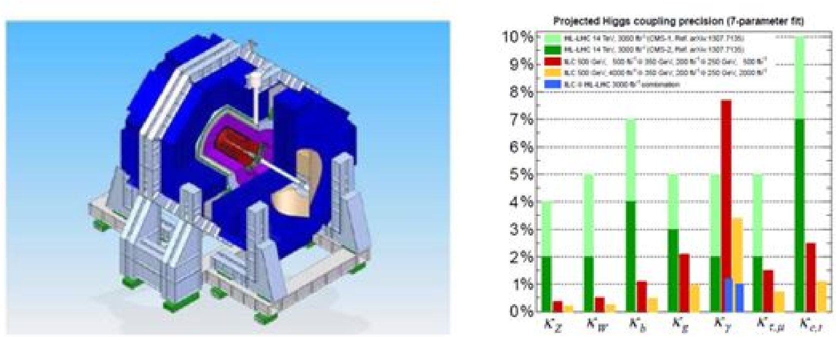


Figure 6: (left) The SiD Detector (right) Higgs couplings projection for ILC and LHC.

Since the writing of the DBD, many further physics and detector optimization studies have been carried out, including the following areas:

- **Pixel tracker option.** Studies of the benefits of a coherent pixel technology implimentation for the vertex detector and silicon tracker combination.

- **Hadron calorimeter** New baseline technology choice for the hadron calorimeter: scintillator/steel instead of RPC/steel. UTA's role in the SiD hadron calorimeter is discussed in the next section.

- **Flux return/muon steel** Redesign of the solenoid flux return to reduce the external field and facilitate easier handling and transportation of steel components.

- **Backgrounds** Studies of the effects of pair, $\gamma\gamma$, and beam muon backgrounds on reconstruction of tracks, jets.

- **Multiplicity studies** Evaluation of the required pipeline depth for the KPix chip - used in all systems except the vertex detector.

- **Foward region** Redesign of the LumiCal, BeamCal, and other components to reflect the new common L* for SiD and ILD.

- **SiD Simulation** A complete reworking of the SiD simulation in the DD4HEP framework - with UTA providing the details of the hadron calorimeter.

Recently, SiD decided to form the SiD Consortium to formalize the membership of this pre-collaboration. SiD now has 30 institutions from the U.S.(55%), Europe (40%) and Asia (5%). We have a set of rules for membership, application procedures for potential new members, and an Institutional Board that meets at each major ILC event. As SiD Spokesperson White has the following roles:

- **Overall Leadership.** Responsible for the physics and technical leadership of the SiD Detector Concept, including appointment of sub-group leaders and promotion of SiD within the Linear Collider and High Energy Physics community within the U.S. and worldwide.

- **Head of the SiD Executive Committee.** Responsible for the overall strategy and guidance of the SiD Consortium, and calling and chairing weekly meetings.

- **SiD Representation** External committees and at ILC conferences. SiD Spokespersons are members of, or report to, a number of external committees such as the Executive Committee of the Physics and Detectors section of the Linear Collider Organization.

- **Americas Linear Collider Committee** White also serves as the at-large universities' representative on the Americas Linear Collider Committee.

In their report, P5 described the ILC physics case as "extremely strong", and support for the ILC Project was included in all scenarios. Earlier a HEPAP Facilities Panel (on which White served) concluded that "The ILC accelerator and detectors enable a research program that will address questions of very great scientific importance, and both the accelerator and the detectors are *absolutely central.*". The Project is currently under evaluation by the Japanese MEXT organization. Recently a U.S. DoE - MEXT Working Group was established, and a list of priority areas identified for focus while the project is under evaluation. There is very strong political, industrial, and community support for the ILC in Japan and a decision is expected in the next 2 years. There has been a series of high-level political and industrial visits by Japanese delegations to the U.S. and White has participated as a representative of the U.S. HEP community. ICFA has restructured the Linear Collider Collaboration with a format designed to carry the project through the next period prior to the final construction decision. If the ILC project is to be realized, the involvement of the U.S. is essential - there simply is not the required cryomodule production capacity in the rest of the world. In order to prepare for potential participation, it is therefore critical that the U.S. maintain its long term intellectual leadership in the project by continued investment in Physics and Detector studies.

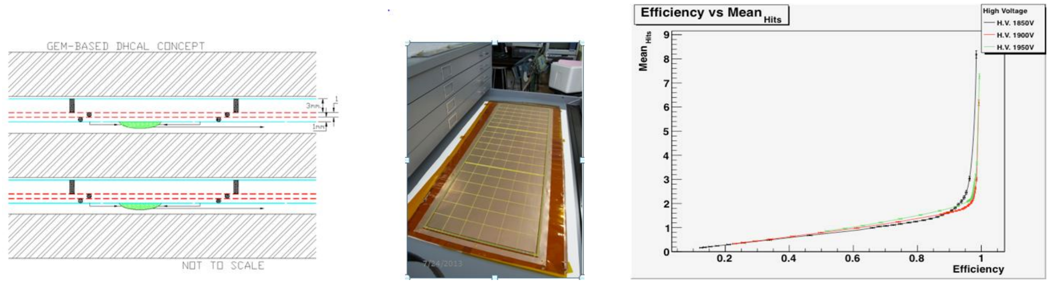
Hadron Calorimetry for SiD, [PI: White] UTA has for several years worked on the development of hadron calorimetry for a future lepton collider. Our graduate and undergraduate students have benefitted significantly from participation in this work, and have made valuable contributions. Future experiments make severe demands on achieving excellent the jet energy resolution. Much of the new physics program for the ILC requires high-precision measurements of jet energies and jet-jet invariant masses. Studies have shown that there is a basic requirement of at least $30\%/\sqrt{E}$, at 100GeV or 3-4% in general for jet energy resolution. This need arises from the requirement for precision Higgs studies, and precision measurements of the masses and other properties of new particles that may be discovered in the next few years at the LHC. A prime physics example of the need for this precision is the reconstruction and separation of hadronic decay modes of W and Z bosons, on an event-by-event basis. Hence there has existed a need for the development of a new type of hadron calorimetry.

The hadron calorimeter is an essential component of the Particle Flow Algorithm (PFA) approach to achieving the required jet energy resolution. The PFA approach has been developed and extensively used in physics studies by both the main ILC detector groups, SiD and ILD. It has also been used in LHC jet reconstruction. Most of the calorimeter development work to provide technical solutions to implementing PFA-orineted systems has been carried out by the CALICE Collaboartion (Ref.). White and Felix Sefkow (DESY) (joined by K. Kawagoe, R. Pschl, and J. Repond) were asked to be the authors/main editors of a Reviews of Modern Physics paper on "Experimental tests of particle flow calorimetry". This paper was published [**?**] in early 2016 and represents a atatement and synthesis of developments of PFA calorimetry. As reflected by this paper, there has emerged a choice of technologies in which to implement the hadron calorimeter for SiD. The technology must support individual charged particle tracking through the calorimeter, allow detailed imaging of energy depositions for track-shower association and separation of closeby showers, while providing good energy resolution for the direct measurement of the energies of neutral particles. White proposed [**?**] a digital hadron calorimeter implementation using Gas Electron Multiplier (GEM) technology [**?**]. GEM offers a robust solution with sufficient amplification in a double-foil configuration, and a thin active layer. This last requirement is important since a typical lepton collider hadron calorimeter would have about forty layers, with the entire system contained inside superconducting coil – the cost of which must be limited.

Figure **??** shows the basic GEM-DHCAL idea introduced by White. The concept of embedding the front-end electronics as part of the active layer has been realized through the development of the KPiX 1024-channel chip by SLAC (with a series of earlier versions also having been tested at UTA). KPiX is specifically designed for the time structure of the ILC beam, and requires a synchronous environment to operate at full efficiency. To implement a full digital hadron calorimeter system would clearly require large area chambers. UTA has developed a series of prototype GEM-DHCAL chambers (see Figure **??**) with fine ($1cm \times 1cm$) cells. A key characteristic of an active layer suitable for use in a digital hadron calorimeter is a low hit multiplicity per track per layer while maintaining a high hit efficiency. Figure **??** shows that our GEM chamber(s) indeed have this desired performance characteristic. The GEM-DHCAL development work has given us very valuable experience with respect to the implementation of the hadron calorimeter for SiD.

The recently adopted, and current, baseline technology for the SiD hadron calorimeter, for detector simulation and physics studies, is small scintillator tiles with SiPM readout, and steel absorber plates. This approach has been the subject of considerable work by CALICE.

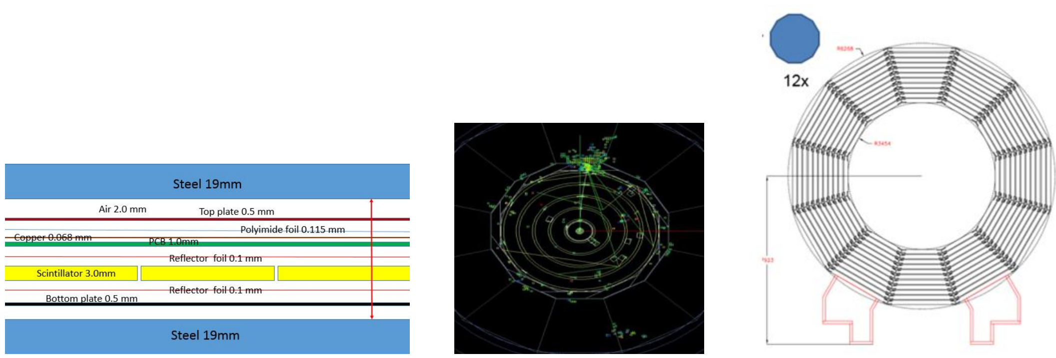
UTA plans to take a leading role within SiD in the development, design, prototyping, and



(a) (b) (c)

Figure 7: (a) GEM Digital Hadron Calorimeter Schematic. (b) large chamber under construction. (c) Multiplicity vs. hit efficiency.

construction of the SiD hadron calorimeter system based on the scintillator/SiPM/steel technology. As a first step, UTA has undertaken the implementation of this technology in the DD4HEP [**?**] framework for the SiD simulation. White has been working with two undergraduate students to specify the details of the hadron calorimeter simulation. Figure **??** shows the CALICE design for an active layer, and the details of its realization for the SiD simulation. CALICE studies have shown that $3cm \times 3cm$ cells yield the required jet energy resolution, and we have used this cell size for SiD. Figure **??** shows the first result for the barrel simulation with a single incident charged particle. Once the full hadron calorimeter simulation is complete, we will make extensive comparisons between our simulations and the results of the CALICE beam tests for a variety of incident particles. SiD has chosen a 12-fold design for the hadron calorimeter (see Figure **??**). taking the CALICE active layer design as input, we will develop a 40-layer module design. This will require the construction and testing of a representative size prototype of an active layer, specification of layer assembly techniques (possibly automated), and mechanical module prototypes.



(a) (b) (c)

Figure 8: (a) SiD AHCAL Barrel layer schematic. (b) SiD AHCAL simulation - single pion. (c) SiD AHCAL Barrel 12-sided structure.

All this activity will be a precursor to the SiD Technical Design Report, the timescale for which depends on the overall progress on the ILC project. We anticipate 2-3 years to complete the TDR, once resources are available.

SiD Timetable of Activities A decision on the ILC Project is expected in 2018. This timetable reflects this anticipated schedule. The activities below reflect White's role as SiD Spokesperson and the planned work at UTA on the SiD hadron calorimeter.

2017

- Guide and pursue the optimization studies for all SiD subsystems
- Initiate and guide further physics studies in response to new LHC results
- Expand the SiD Consortium, particularly in Europe and Asia
- Work with the U.S.- Japan Caucus and the ALCC to prepare the case for U.S. support of the ILC
- Represent SiD at national and international Linear Collider conferences
- Complete the full simulation of the SiD baseline hadron calorimeter, and verify performance vs. CALICE results
- Develop initial hadron calorimeter barrel and endcap module concepts

2018

- Continue the first five tasks from 2017
- Work with Japanese colleagues to provide input from SiD to inform the anticipated ILC Project decision by MEXT
- Begin the framework for the SiD Technical Design Report
- Develop production and assembly procedures for SiD hadron calorimeter actve layers, and module integration

2019 Subject to the ILC Project proceeding:

- Continue the general tasks from 2017/18
- Prepare the SiD Experiment initial submission in response to anticipated call for expressions of interest/proposals
- Establish initial areas of responsibilities for SiD member institutes in the transition from the SiD Consortium to the SiD Collaboration
- Begin full engineering design and prototyping for SiD hadron calorimeter modules

Research at the Energy Frontier

Executive Summary

The Intensity Frontier (I.F.) group of the University of Texas at Arlington started in 2014 with 0.5 FTE of PI Jaehoon Yu and of PI Amir Farbin aiming for a balanced program between US-based and non-US based experiments. In order to continue to build a strong I.F. program, the group recently hired a full time I.F. junior faculty, Dr. Jonathan Asaadi. While Farbin has decided to transition back to the Energy Frontier (E.F.), the overall strength of the group has grown double to two full PI's with the successful transition of Yu to full time I.F.

Beyond the addition of a new faculty member, the UTA I.F. group has made significant contributions to the LArIAT, LBNE/DUNE, and MiniBooNE experiments. Farbin played a key role of deputy computing coordinator for the DUNE project and Yu has served as a co-convener for the LBNE R&D Coordination group. Yu's role has evolved to a co-convenership of the DUNE Beyond the Standard Model physics group in September 2015. UTA also hosted of the first off-Fermilab-site DUNE collaboration meeting in January, 2016, in which over 150 collaborators participated.

Farbin and Yu have been supervising a student who has been contributing to the beam-dump dark matter search with first results expected in fall 2016. Asaadi has continued his roles on MicroBooNE, serving as the convener of the Astro-Particle and Exotics group through August 2016 and a lead TPC-Expert for the experiment. Asaadi has also played a leadership role on LArIAT serving as the analysis coordinator in 2015 and 2016 leading to the first measurement of the π^--Argon cross-section and now will transition to serve as a co-spokesperson (starting Fall 2016). The UTA group has also joined the SBND and the ICARUS experiment (with Yu as institutional board member) and has been contributing to the refurbishment of the light detection system with the hire of a new post-doctoral researcher (an existing ICARUS collaborator), Dr. Andrea Falcone.

In this document, we propose to complete the ongoing effort on MiniBooNE (Yu), and continue/add significant contributions to SBND (Asaadi, Yu), MicroBooNE (Asaadi), ICARUS (Asaadi, Yu) and the Deep Underground Neutrino Experiment, DUNE (Asaadi, Yu) with vital contributions to the two protoDUNE projects. These experiments are carefully selected to leverage our group's growing technical and analysis expertise utilizing liquid argon time projection chambers. Moreover, in order to accomplish the work laid out in this proposal, the UTA group will leverage Asaadi's start-up to provide an additional (beyond what is requested here) post-doctoral researcher (Dr. Andrea Falcone) in year one and two of this proposal. Dr. Falcone will play a leadership role on the ICARUS and SBND experiments during construction, installation and commissioning, moving to Fermilab in time with the transfer of the refurbished ICARUS detector.

The work on MiniBooNE is limited to data analysis using the beam dump data taken in 2014 for a low mass dark matter search. This is anticipated to complete in the early stage of this renewal proposal period with the graduation of Sepideh Shahsavarani, Farbins Ph.D. student. This student will stay on the I.F. program for another two years till she completes her Ph.D. under the joint advisement of Farbin, Yu, and Asaadi and is expected to contribute to the other I.F. efforts of the group. Concurrently, a second graduate student (Zack Williams) will be funded via Asaadi's start-up to allow for a transition of research duties upon Shahsavarani's graduation. Other new graduate students are being trained to take part in our I.F. program but will be supported through other funding sources available at the university until resources become available with the graduation of senior students. The selection of the graduate students will be carefully managed to maximize the available resources for their degree programs. Asaadi will continue to play a leadership role on LArIAT together with Yu on data analysis and operations with the expected winding down of the project in the next 1-2 years.

UTA Strategic Plan

The UTA group will have contributions and responsibilities across the Fermilab the short-baseline neutrino (SBN) program as well as the long-baseline neutrino (LBN) program. The primary strategic goal of the group throughout the period of this proposal is to contribute to the success of the construction and execution of these experiments. We aim to position ourselves to make major contributions to the DUNE project by playing leadership roles in the design and construction of the single and dual phase prototype detectors, protoDUNE's at CERN neutrino platform. This work is intended to allow UTA to be a world leading institution for the construction and data analysis of the DUNE detector. Synergistic with this goal, our active participation in the construction, commissioning and operation of the SBN experiments - MicroBooNE, SBND, and ICARUS - allows us to enhance our expertise in LArTPC technology, produce valuable physics results, and gain experience in near/far oscillation analyses utilizing the data from these detectors.

Among the various tasks described below, we consider protoDUNE to be under the most restrictive timeline and deserve immediate attention early in the period of this renewal proposal. Since the availability of charged particle beams at CERN's neutrino platform is dictated by the CERN accelerator complex upgrade schedule, having the protoDUNE detectors ready before the shutdown of the CERN accelerators at the end of 2018 is critical. Moreover, the protoDUNE projects are on the critical path for the success of the U.S. flagship experiment, DUNE. The SBN experiments are also seen by the UTA group as a high priority, but given that Fermilab will continue provide beams to these experiments through at least 2021, they are not on as critical of a schedule driven path.

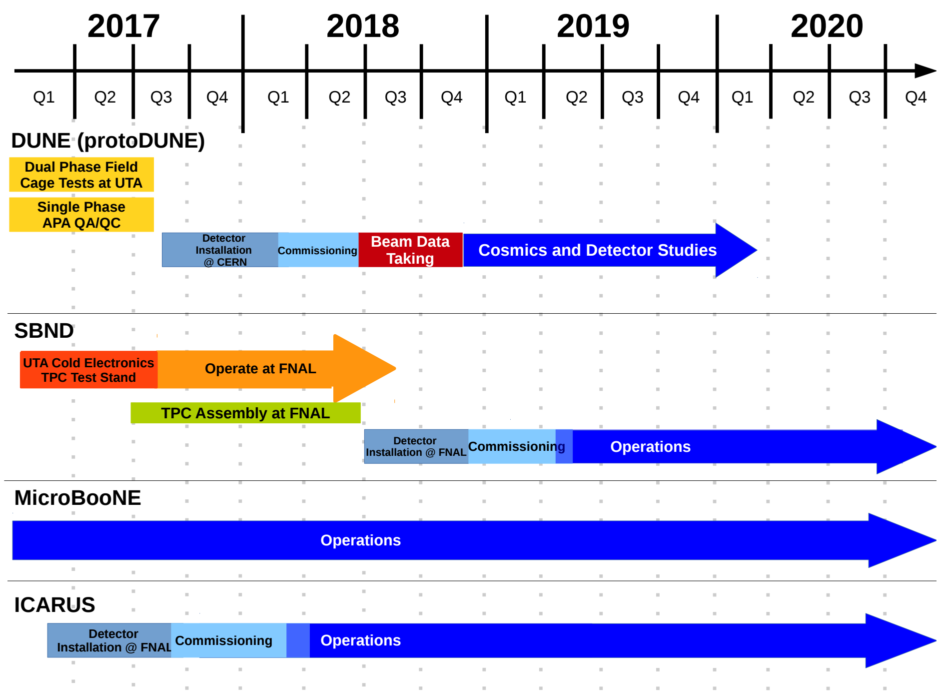


Figure 9: Timeline of the strategic projects proposed .

Figure **??** attempts to summarize the timeline for the projects which will be executed during the funding period of this proposal. These projects are described in greater detail in subsequent sections. The strategic goal is to have Asaadi focus on the short and mid-term experiments such as MicroBooNE and SBND with a smaller portion of his time on ICARUS and DUNE initially and then ramping this effort over time. Meanwhile, Yu will focus on the long and mid-term experiments such as DUNE and ICARUS with a gradually increasing portion over time on the whole SBN program. This will allow our group to maintain a constant level of contribution from both the PI's and the post-doctoral and graduate researchers on all four experiments.

Tables **??** summarizes the projects and associated P.I. who will take a lead role on this proposal and where the effort will be located. The division of projects and P.I. effort is designed to find synergy between the timeline when each effort is to take place. This will allow Asaadi and Yu to maximize their impact across the neutrino program.

IF Summary of Proposed Work

Experiment	Project	Location	Lead PI
DUNE	protoDUNE SP-APA QA/QC and installation	UTA/CERN	Asaadi
	BSM Physics	UTA	Yu
	protoDUNE DP-FC Construction	UTA/CERN	Yu
SBND	Cold Electronics TPC Test-stand	UTA/FNAL	Asaadi
	Detector Construction, Installation, and Commissioning	FNAL	Yu
	Cross-Section Data Analysis	UTA/FNAL	Asaadi
MicroBooNE	TPC Detector Expert	UTA/FNAL	Asaadi
	Detector Operations	UTA/FNAL	Asaadi
	Cross-Section Data Analysis	UTA/FNAL	Asaadi
ICARUS	Detector Installation and Commissioning	FNAL	Asaadi
	NuMI Off-Axis Cross-Sections	UTA/FNAL	Yu
MiniBooNE	Beam Dump Dark Matter Search	UTA/FNAL	Yu

Table 5: Overview of the UTA projects across the Intensity Frontier

Table **??** summarizes the projects and associated personnel resources that will execute the research described in greater detail in the subsequent sections. The post-doctoral effort is divided between the DUNE and SBN programs with an additional post-doctoral researcher coming from Asaadi's start-up funds. The graduate students will have hardware and data analysis on DUNE, but will focus on the SBN for their thesis analysis.

The Short Baseline Neutrino (SBN) Program

The SBN program, described in more detail in Section **??**, aims to conclusively address the experimental hints of sterile neutrinos through the utilization of three LArTPC detectors. The SBN plays an essential component for our group by continually producing physics results throughout the construction period of DUNE experiment and contributing to the development of LArTPC technology. Below we outline the projects associated with the SBN program and reference the sections where the work is described in more detail.

SBND: Given the large overlap of the collaborators between MicroBooNE and SBND, Asaadi is well recognized in the collaboration. Therefore, Asaadi will be the institutional representative to the collaboration and lead the effort on SBND. Yu is in discussions with the SBND management for his joining to the collaboration prior to the start of this funding period in 2017 and will contribute to the efforts outlined below and presented in greater detail in Section **??**.

- **Cold Electronics TPC Test-stand:** Section **??**

Summary of PI, Postdoc, and Graduate Personal

Personnel	Associated Task	Years Supported	Source of Support
Postdoc 1 (Animesh Chatterjee)	protoDUNE SP/DP SBND Operations and Data Analysis ICARUS Operations and Data Analysis	2017 - 2020	UTA Base Grant
Posdoc 2 (TBN)	protoDUNE SP/DP MicroBooNE Operations and Data Analysis SBND Cold Electronics Test Stand	2017 - 2020	UTA Base Grant
Postdoc∗ (Andrea Falcone)	ICARUS/SBND Installation and Commissioning MicroBooNE Operations and Data Analysis	2017 - 2019	UTA Start-up funds
Graduate Student 1 (Garrett Brown)	protoDUNE SP/DP SBND/ICARUS Operations and Data Analysis	2017 - 2020	UTA Base Grant
Graduate Student 2a (Sepideh Shahsavarani)	MiniBooNE Data Analysis protoDUNE DP	2017 - 2019	UTA Base Grant
Graduate Student 2b * (Zack Williams)	SBND Cold Electronics Test Stand, SBND Construction, Installation, and Commissioning MicroBooNE Operations and Data Analysis	2017 - 2019 2019 - 2020	UTA Start-up funds UTA Base Grant
Prof. Jonathan Asaadi	SBN/DUNE	2017 - 2020	UTA Base Grant
Prof. Jae Yu	DUNE/SBN	2017 - 2020	UTA Base Grant

Table 6: Table summarizing the personnel working on the project described in this proposal. Note: Personnel marked with "*" denote that their effort is supported for some phase of the project utilizing Asaadi's start-up funds. This is done to maximally leverage the UTA group across both DUNE and the SBN program.

- **Detector Construction, Installation, and Commissioning:** Section **??**
- **Cross-Section Data Analysis:** Section **??**

MicroBooNE: Asaadi has been an essential member of the construction, commissioning, operation and data analysis on MicroBooNE. With Asaadi being a young-tenure track faculty member, it is essential for him to be able to produce physics results in the first years of the proposal. Given this, Asaadi will focus on operations and data analysis outlined below and presented in greater detail in Section **??**.

- **Detector Operations and TPC Detector Expert:** Section **??**
- **Cross-section Data Analysis:** Section **??**

ICARUS: With the inclusion of the ICARUS experiment, this completes the short-baseline neutrino oscillation experiment utilizing a low energy neutrino beam. For this reason, the UTA group deems the success of ICARUS as an essential component of the SBN. In line with that, our group has joined the experiment as a member with Yu as the institutional board representative as one of the handful of U.S. groups to participate in it. Moreover, we have been utilizing Asaadi's start-up funds to support a post-doctoral researcher to help lead the refurbishment and integration of ICARUS. During the funding period here our efforts include the following, presented in greater detail in Section **??**.

- **Installation, Commissioning, and Detector Operations:** Section **??**
- **NuMI Off-Axis Cross-Sections:** Section **??**

Deep Underground Neutrino Experiment (DUNE)

DUNE aims to address the questions of the neutrino mass hierarchy and CP-violation in the lepton sector by measuring the asymmetry between appearance of electron neutrinos from a beam of muon neutrinos ($P(\nu_\mu \rightarrow \nu_e)$) compared to the appearance of electron antineutrinos from a beam of muon antineutrinos and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$) as well as the precise measurement of the ν_e energy spectrum measured at the far detector. The UTA group aims to play a major role in this U.S. flagship experiment in both single phase and dual phase protoDUNE experiments.

protoDUNE: The UTA group will be contributing to both the protoDUNE Dual Phase (DP) and Single Phase (SP) detectors. Asaadi and Yu expect to play a major role in various detector component construction, installation, and commissioning as well as data taking during the first two years of this proposal. This work will lay the foundation to contributing to the DUNE experiment and is described in greater detail in Section **??**.

- **ProtoDUNE Single Phase-Anode Plane Assembly QA/QC:** Section **??**
- **ProtoDUNE Dual Phase-Field Cage Construction:** Section **??**

DUNE Beyond the Standard Model Physics: UTA has been a leading participant in searching for low mass dark matter in high intensity proton beams from the start of the I.F. group in 2014. For this work, Yu has been leading the BSM physics working group of DUNE since September 2015 and has grown the group to play a significant role within the collaboration. Yu plans on ensuring various BSM topics be included in the DUNE Technical Design Report to be released in summer 2019.

With this strategic plan in place, the activities proposed aim to ensure synergy between the SBN and LBN efforts and to optimize our use of resources. What follows is a broad introduction to the compelling physics which motivates this research program as well as a more detailed sketch of the program of work which is intended to be executed in the intensity frontier.

Physics Introduction

The discovery that neutrinos undergo oscillation in their flavor, and thus are massive particles, serves as one of the first pieces of evidence for physics beyond the Standard Model (SM) of particle physics. The prevailing description of neutrino oscillations provided by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix characterizes the flavor change as a result that the neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) are a linear combination of the neutrino mass eigenstates (ν_1, ν_2, ν_3). The rotation from the mass eigenstates to the flavor eigenstates is governed by three angles $\theta_{i,j}$, where i and j correspond to the mass eigenstates with $i < j$, and a phase δ which determines magnitude of charge-parity (CP) violation within the neutrino sector. In addition, the flavor change of the neutrinos depends on the ratio of neutrino energy and the distance traveled by the neutrino (often referred to as the baseline) as well as the difference in the square of the mass eigenstates Δm^2_{ji}. Neutrinos produced in the atmosphere [**?**, **?**, **?**], in nuclear reactors [**?**, **?**, **?**], in the sun [**?**, **?**, **?**], as well as in man-made particle accelerators [**?**, **?**, **?**] have been used to study the phenomenon of neutrino oscillations. The exact ordering of the neutrino mass states, known as the mass hierarchy, as well as the size of the CP-violating phase δ are, as yet, unknown. These quantities remain one of the last major pieces of the Standard Model of particle physics and offer the opportunity to answer such fundamental questions as:

1) **What is the origin of the matter/antimatter asymmetry in the universe?**

2) **Do we understand the fundamental symmetries of the universe?**

3) **Is the three-flavor paradigm of the Standard Model for neutrino oscillation the accurate description for neutrino interactions?**

Into this experimental landscape, there exists a set of series of experimental measurements which suggest that the three-flavor paradigm of neutrino oscillations is incomplete. Two general classes of anomalous observations may point to additional physics beyond the SM in the neutrino sector.

- **The disappearance signal in low energy electron anti-neutrinos from reactor neutrino experiments [?] *("Reactor Neutrino Anomaly")* and Mega-Curie radioactive electron neutrino sources in Gallium [?, ?] *("Gallium Anomaly")***

- **The electron-like excess from muon neutrino (and anti-neutrino) particle accelerators *("LSND/MiniBooNE Anomaly")* [?, ?]**

Neither of these anomalies can be accounted for by the standard three-flavor oscillations of the SM and may hint at the existence of additional neutrino states with larger mass difference ($\Delta m^2_{new} \geq 0.1eV^2$) which participate in the mixing of the flavour states (referred to as "sterile neutrinos"). Definitive evidence of the existence of new neutrino states would be a revolutionary discovery with broad implications for both particle physics and cosmology. Moreover, in order for future accelerator based neutrino experiments to disentangle the mass hierarchy and search for CP-violation, the oscillation framework must be concretely known and precisely measured.

Liquid Argon Time Projection Chambers (LArTPCs) offer fine-grain tracking as well as powerful calorimetry and particle identification capabilities making them ideal detectors for studying neutrino-nuclei interactions. When a neutrino interacts with an atom in the liquid argon multiple final state charged particles as well as electromagnetic objects (such as photons and electrons) can be produced. When the charged particles traverse the liquid argon they produce ionization which drifts along the electric field inside the TPC towards a set of wire planes which are oriented at different angles with respect to each other. The drifting ions produce an electric signal on the wire planes, which is read out of the detector. By knowing the drift speed of the ions and the timing of the interaction as well as the deposition of charge on the wires a three-dimensional image of the interaction can be reconstructed. The information of the charge deposition in addition to the topological information allows for particle identification and calorimetric reconstruction. This allows, for example, the ability to disentangle electron initiated electromagnetic showers from photon initiated showers by looking at the displacement in the start of the electromagnetic shower from a primary vertex as well as analysing the energy deposited in the first centimetres of the shower (dE/dX), shown schematically in Fig. **??**.

For these reasons, this detector technology has been chosen for both the study of neutrino oscillations over relatively short baselines (< 1 km) and long baselines (> 1000 km). The combination of millimeter scale tracking capabilities, outstanding calorimetry through a fully active/sampling detector, and powerful particle identification made by combining the ionization along the particle trajectory (dE/dX) and the topological information, have made LArTPCs the premier neutrino detector technology choice for the future.

Recently, a great deal of interest has been paid to the possibility of studying the models for Low-mass Dark Matter (LDM) production at low-energy, fixed-target experiments (see Refs. [**?**, **?**, **?**, **?**]. High flux neutrino beam experiments, such as DUNE, have been shown to provide coverage of DM + mediator parameter space which cannot be covered by either direct detection

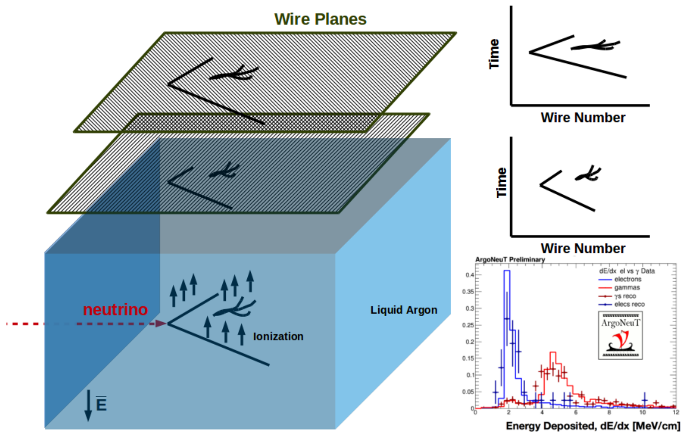


Figure 10: Operating principals of LArTPC detectors.

or collider experiments. Upon striking the target, the proton beam can produce the dark photons either directly through $pp(pn) \rightarrow \mathbf{V}$ or indirectly through the production of a π^0 or a η meson which then promptly decays into two Standard Model photons of which one couples to the heavy dark photon. For the case where $m_V > 2m_{DM}$, the dark photons will quickly decay into a pair of DM particles. These relativistic DM particles from the beam will travel along with neutrinos to the DUNE near detector.

The DM particles can then be detected through neutral-current like interactions either with electrons or nucleons in the detector. Since the signature of DM events looks just like those of the neutrinos, the neutrino beam provides the major source of background for the DM signal. Several ways have been proposed to suppress neutrino backgrounds by using the unique characteristics of the DM in the beam. Since DM will travel much slower than the neutrinos with much higher masses, the timing of the DM events in the near detector. In addition, since the electrons struck by DM will be much more forward direction than those from neutrino interactions, the angle of these electrons may be used to reduce backgrounds, taking advantage of fine angular resolution DUNE near detector can provide. Finally, a special run can be devised to turn off the focusing horn to significantly reduce the charged particle flux that will produce neutrinos. If DUNE near detector were LArTPC, since the entire detector volume will be active, the effective number of DM events detected will be much higher with the detector of the same mass.

Given these new theoretical background, high intensity proton beams that are needed for DUNE will provide sensitivity to mass ranges inaccessible at direct-detection experiments such as CDMS and XENON [**?**]. We believe this effort has the potential of expanding DUNE's physics motivation beyond neutrinos, super-novae, and proton decays. For this work, Yu and the postdoctoral fellow, Chatterjee have been working on integrating the existing MadGraph c [**?**] based simulation package into the existing LBNE/DUNE fast simulations. A version of this package has already been prepared for Non-Standard Model Neutrino Interaction studies for the DUNE BSM physics group. Our Ph.D. student has been working on data analysis of MiniBooNE beam dump experiment for feasibility study.

PI Summary: Jonathan Asaadi

Part III
The Fermilab Short-Baseline Neutrino Program

The conclusive redress of the experimental hints of sterile neutrinos thus becomes high priority for the field of neutrino physics. The Fermilab Short-Baseline Neutrino (SBN) program, shown in Fig. **??**, offers the unique opportunity to definitely address the "LSND/MiniBooNE" anomaly through the utilization of three liquid argon time projection chambers (LArTPCs) detectors and the decade old and well characterized Booster Neutrino Beam (BNB). The SBN program offers a rich physics program with the ability to perform the most sensitive search to date for the existence of sterile neutrinos at the eV mass-scale. The Short-Baseline Near Detector (SBND) will be a new 112 ton LArTPC and serve as the near detector to the SBN program located 110 meters downstream of the BNB target. SBND will measure the un-oscillated neutrino flux from the BNB and enable searches in both the neutrino appearance and disappearance channels. The MicroBooNE detector is a 89 ton active mass LArTPC located 470 meters downstream of the BNB target (just in front of the MiniBooNE experiment). MicroBooNE serves as the pioneer LArTPC experiment on the BNB and will lay the groundwork for the oscillation analysis. The far detector will utilize the upgraded ICARUS-T600 experiment, previously installed and operated at the Gran Sasso Laboratory, and will be located in a new building 600 meters from the BNB target. ICARUS's large detector mass provides the SBN program with the experimental sensitivity to definitively search for the existence of eV mass-scale sterile neutrinos.

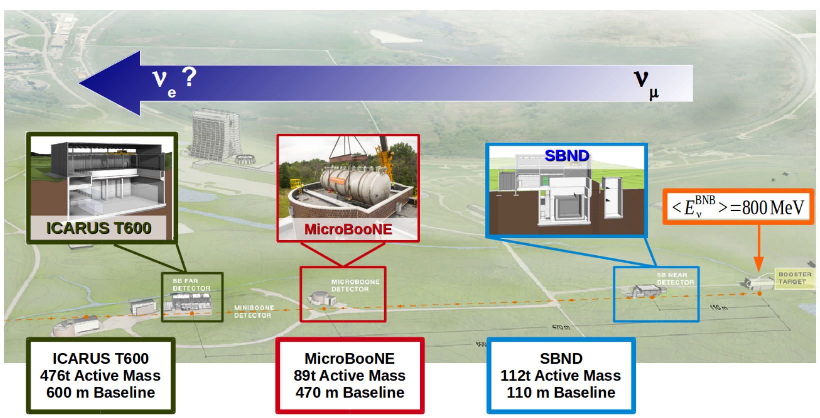


Figure 11: Overview of Fermilab's Booster Neutrino Beamline (orange dashed line) campus with the location and description of the three SBN detectors.

The first experiment to observe an electron-like excess in the electron neutrino appearance channel was the LSND experiment [**?**] at Los Alamos National Laboratory. LSND used a decay-at-rest pion beam to produce muon anti-neutrinos ($\bar{\nu_\mu}$) in the energy range between 20-53 MeV and a distance of 30 meters from the liquid scintillator based detector. After five years of running, LSND reported an excess electron like events corresponding to a 3.8σ evidence for $\bar{\nu_\mu} \rightarrow \bar{\nu_e}$ oscillations occurring with a Δm^2 of $\sim$ 1eV^2. This suggests an oscillation beyond the SM three flavor neutrino oscillation which occurs at an L/E_ν $\sim$ 1m/MeV. To test for the appearance of this anomalous oscillation, the MiniBooNE experiment [**?**] at Fermilab utilized 700 MeV muon neutrinos produced from the Booster Neutrino Beam at a baseline of 540 meters (thus giving a similar L/E_ν to LSND). MiniBooNE identified muon and electron neutrino interactions by their characteristic Cherenkov rings inside a scintillator detector. As shown in Figure **??**, in ten years of data taking in both neutrino and anti-neutrino running MiniBooNE observed a 3.5σ excess in ν_e candidates and a 2.8σ excess in $\bar{\nu}_e$ candidates. This excess of events observed by MiniBooNE can be due to electrons from ν_e interactions as well as from single photon backgrounds, since these two final states are indistinguishable to the Cherenkov imaging detector.

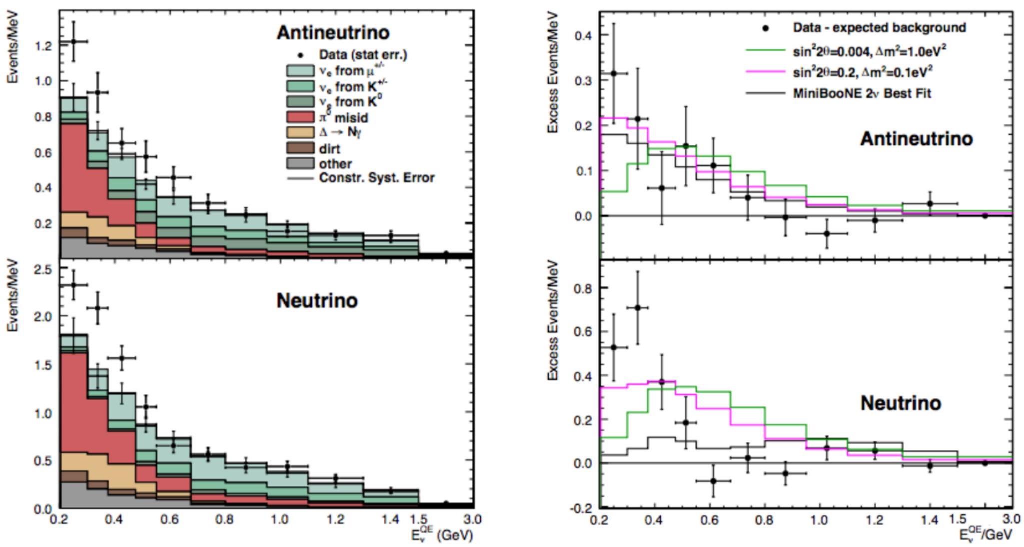


Figure 12: Left: Electron anti-neutrino ($\bar{\nu}_e$) and neutrino (ν_e) candidate events shown with the predicted backgrounds in MiniBooNE. Right: Background subtracted event rates in MiniBooNE as well as different sterile neutrino models overlayed with the data.

A common interpretation of this data is to posit the existence of one or more additional sterile neutrino states with masses at or below the eV range. This interpretation requires mixing of the sterile state(s) with both the electron and muon neutrino flavor states. Constraints from sterile mixing from ν_μ and neutral current disappearance data [**?**, **?**] leads to significant tension between the ν_e appearance data and the ν_μ disappearance data.

To disentangle the open question of how to interpret the LSND/MiniBooNE anomaly, both an excellent neutrino detector technology as well as a robust experimental program is required. The liquid argon time projection chamber (LArTPC) offers physics capabilities ideally suited for the study of neutrino interactions. By combining millimetre scale tracking capabilities, outstanding calorimetry by having a fully active/sampling detector, and powerful particle identification made by combining the ionization along the particle trajectory (dE/dX) and the topological information, LArTPCs have been chosen to be the premier neutrino detector technology.

10 Short-Baseline Near Detector (SBND) (PI: Asaadi, Yu)

The SBND experiment is designed to build upon the many years of LArTPC R&D and serve as a test-bed for the future long baseline neutrino experiment. As shown in Figure **??**, the conceptual design is to construct a membrane cryostat in a new on experiment hall located 110 meters from the BNB target. The cryostat will house the full TPC consisting of one central cathode plane assembly (CPA) and four anode plane assemblies (APAs) which will have three wire planes with three millimetre spacing (similar to the ICARUS design) and the first two induction planes oriented at $\pm 30°$ to the beam axis and the final plane oriented vertically. SBND will be a 5.0 m × 4.0 m × 4.0 m (l×w×h) TPC with 112 tons of active volume. SBND will also have a light detection system based on a hybrid of the ICARUS cryogenic PMT's and the proposed DUNE light-guide with silicon photomultiplier (SiPMs) on the end. This light detection system will be embedded behind the APA structure on both sides of the TPC.

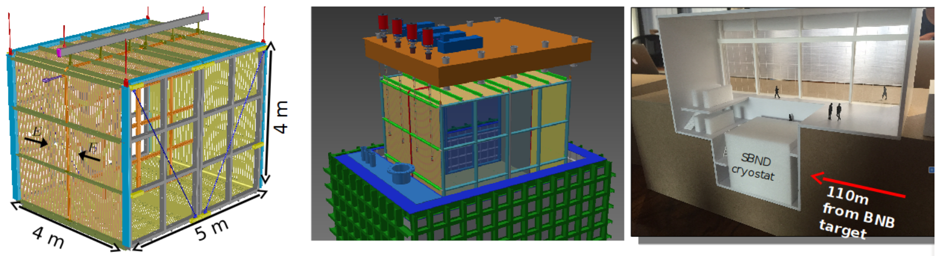


Figure 13: Conceptual design of the SBND TPC, cryostat, and detector hall.

One new unique aspect of the SBND detector will be the inclusion of the entire front end readout chain being moved into the liquid argon. The front end electronics are composed of 16-channel analogue front end ASIC which provides amplification and shaping, a 16 channel analogue to digital converter ASIC which provides digitization, buffering, and multiplexing as well as a cold FPGA which provides second multiplexing and voltage regulation. This technical improvement in readout electronics will provide improved signal-to-noise as well as allow for the development of an efficient zero-suppression scheme implemented in the FPGA to greatly reduce the total data volume. Many bench tests of the readout electronics have been performed and shows excellent performance, however a full integration test with an operating TPC has not been successfully performed (given the many problems seen by the 35ton prototype) and serves as an absolutely necessary service task the UTA group is planning to spearhead.

10.1 Cold Electronics Teststand

Figure **??** shows a schematic of what this test-stand would look like utilizing the "Blanche" cryostat currently installed at the Proton Assembly Building (PAB)at Fermilab. This cryostat is engineered to have delivered purified liquid argon into the cryostat as well as circulate, re-condense, and purify boil-off argon. A duplicate of this cryostat is currently being built and will be delivered in late 2016 to UTA. This cryostat will work in conjunction with the liquid argon purification system currently in operation at UTA. This system is built using start-up funds from PI Asaadi and will allow UTA to play an important role in the ability to do detector R&D in the coming years.

Inside this cryostat, a small scale TPC equipped with prototype cold readout electronics from SBND installed along side a pair of light guide bars can be deployed and readout through a 14" inch cold signal feedthrough as designed for the SBND detector. External to the cryostat, scintillator paddles can be positioned to act as an external trigger. Since the cryostat is a copy of an existing one at FNAL, upon its completion the top flange and TPC detector will be shipped to FNAL for longer term use for SBND (and potentially other future LArTPCs). Additional material costs, such as the electronics, power supplies, and cabling are expected to be provided by SBND project funds and Prof. Asaadi's start-up funds.

This test-stand can allow for a robust set of tests for the integration of many new readout components prior to their deployment in the experiment. This critical step was not taken during the MicroBooNE assembly and as a result a number of problems with the readout electronics were

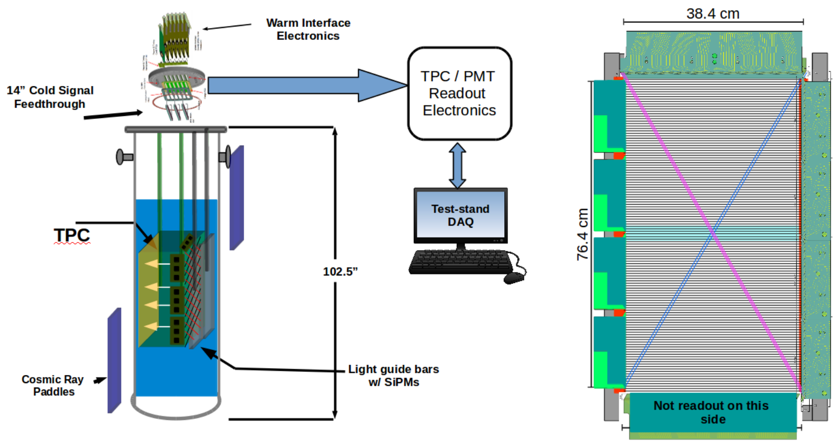


Figure 14: Conceptual design of the SBND cold electronics vertical slice test-stand. Integration of both cold or warm electronics, light collection system, cosmic ray paddles, as well as warm interface electronics allows for complete testing of the entire readout system prior to deployment in the experiment and a platform for DAQ debugging outside the actual the experiment. The current design has 768 channels (256 collection, 512 induction) utilizing six SBND designed motherboards.

not detected in advance of attempting to commission the detector. These problems included the bias voltage line for the TPC wires behaving in an unexpected way and causing pick-up noise to be seen on the electronics, cross-talk between the light detection system and the TPC readout, and the incorrect configuration of electronics settings because of software bugs. While many of these issues were able to be solved during the commissioning phase, they slowed the progress of transitioning to data taking and caused unnecessary harm to the experiment. Moreover, this test-stand will provide a platform for testing and debugging of the DAQ software and readout electronics configuration without interrupting the operation of the SBND experiment.

The postdoctoral researcher and graduate student supported by this work will be developing the readout software into a common DAQ software package used by other LArTPC based experiments known as the artDAQ framework. This common platform ensures that the work done by those supported in this proposal can have a greater impact on future planned LArTPCs as well as allowing them to benefit from the work that has already been done by others.

Finally, such a test-stand can provide an R&D platform for long term testing of future readout components as well as software development for online triggers and zero-suppression schemes without risking downtime on operating neutrino detectors. The trigger schemes envisioned include utilizing multi-core graphical processing units to do online TPC based triggering for rare search events such as proton decay and supernova neutrino triggering. Moreover, by providing a platform for the development of LArTPC's DAQ systems into a common platform such as artDAQ, a greater push to the integration of the data, simulation, and analysis into one common software platform can be accomplished. The events processed utilizing the artDAQ software are immediately readable by the common liquid argon software framework known as LArSoft. Thus, working on this system and the associated neutrino detectors DAQ help promote the use of a common software framework.

10.2 Construction, Installation, and Commissioning

The UT Arlington group is positioned to play a major role in the construction and commissioning of the SBND detector and data acquisition system. Given the groups experience from MicroBooNE and

LArIAT (where Asaadi played a lead role of TPC expert during construction, commissioning, and operations for both experiments) as well as the experience of the post-doctoral researchers already with the group (Falcone from ICARUS and Chatterjee from LArIAT) UTA hopes to offer hands on leadership during the construction phase.

During the construction phase for the TPC (foreseen in mid 2017 through mid 2018), Falcone is expected to be in residence at FNAL and will be spending 50% of his time on SBND. During that same time, a to-be-named post-doc will join him at FNAL with a focus on SBND TPC construction. Having these two present will allow for a rapid ramp-up on the project. At the same time, the Cold-Electronics test-stand is expect to be moved from UTA to FNAL for operations. The graduate student Zach Williams is expected to go with this project in the summer of 2017 and be in residence at FNAL. With his time already spent on this project, continuing to contribute to the DAQ development and aiding in the construction and installation of the cold electronics on the TPC is a natural fit. PI Asaadi is expecting to spend a significant portion of his time at FNAL during the second half of 2017 to help oversee these activities and contribute to the construction and phase.

Following the construction and installation phase, one post-doc and one graduate student are expected to stay with the SBND experiment a significant portion of their time to play a role as detector experts during the commissioning and initial data taking. The aim here is to share their expertise across the SBN program, but to have a reliable source of experts in residence at FNAL for SBND.

10.3 SBND Data Analysis

SBND will provide important physics measurements during its early operations in addition to providing an overall flux normalization to the key SBN oscillation analysis. Critically, SBND will collect very quickly statistics to confirm the nature of the MiniBooNE excess as measured by MicroBooNE. If MicroBooNE were to confirm the MiniBooNE excess as originating from electron-like sources, SBND could quickly measure if there is an oscillation component to the electron-like signal by measuring the rate as seen in the near detector. Conversely, if MicroBooNE were to determine the MiniBooNE excess as originating from photon-like sources, SBND can cross-check if the source is an unaccounted for beam like background or coming from cosmogenic like backgrounds. Regardless of the outcome, SBND will play a critical role in quickly collecting high statistics data as the near detector to the SBN program.

SBND will also provide critical neutrino cross-section measurements at a statistical precision unprecedented by any other LArTPC. SBND will collect approximately two million neutrino interactions per 2.2×10^{20} protons on target (roughly one year of running). With 1.5 million ν_μ charged current interactions and 12,000 ν_e charged current interactions in one year. With such statistics, many precision cross-section measurements (e.g. double differential) become possible and improvements on first and second generation analyses from MicroBooNE can be explored in the first year of data taking.

Furthermore, by collecting approximately 100,000 NCπ^0 events per year a full characterization of the leading background cross-section to the long baseline CP-violation analysis can be performed. The elimination of this systematic uncertainty in the cross-section will improve the experimental reach of the future planned DUNE experiment.

11 Micro-Booster Neutrino Experiment (MicroBooNE) (PI: Asaadi)

The MicroBooNE experiment serves as the first detector deployed at the SBN facility and represents the next step in LArTPC technology. MicroBooNE is a 10.3 m $\times$ 2.5 m $\times$ 2.3 m TPC with 89 tons of active volume. The TPC, shown in Figure **??**, has three instrumented wire planes with the first two induction planes oriented at $\pm 30^{\circ}$ to the beam axis and the final plane oriented vertically. Both the pitch and wire spacing is chosen to be 3 mm, which provides superb resolution for imaging interactions inside the detector. Additionally there are 32, 8" cryogenic photomultiplier tubes (PMTs) which provide the t_0 for an interaction by recording the scintillation light produced when the charged particles interact in the argon.

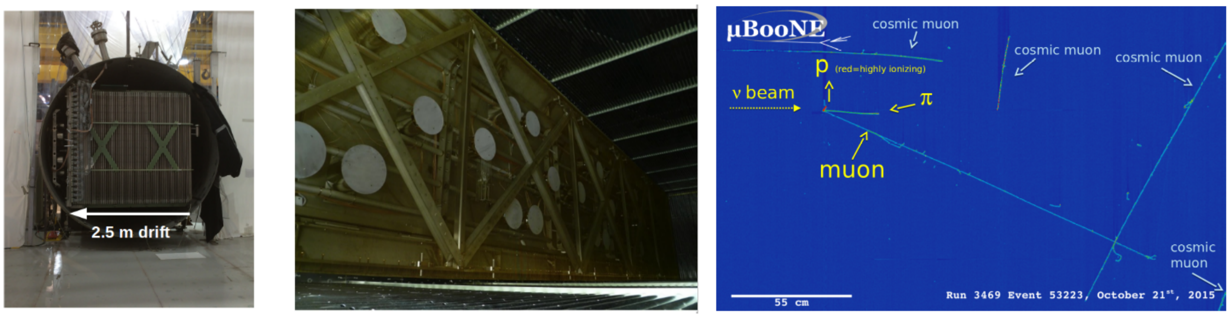


Figure 15: (Left) The MicroBooNE TPC after installation inside the cryostat. (Center) long exposure view of the inside of the TPC. The acrylic disks coated in wavelength shifting material which sit directly in front of the PMTs can be seen behind the wire planes. (Right) One of the first identified neutrino events utilizing the light and charge readout.

In the summer of 2015 MicroBooNE was filled with liquid argon and began commissioning. During this initial commissioning the drift high voltage was brought to $\sim 45\%$ its nominal value and immediately cosmic ray tracks and scintillation light were able to be seen. With the rapid success of the system, MicroBooNE has now transitioned from commissioning to neutrino data taking starting in October of 2015. Figure **??** shows an example of an automatically identified neutrino candidate event collected by utilizing both light and charge information.

One of the most compelling measurements MicroBooNE will make is to confirm or refute the nature of the MiniBooNE low-energy electron neutrino excess. Utilizing the particle identification powers of the LArTPC (specifically the dE/dX discrimination), MicroBooNE will be able to differentiate the electron-like electromagnetic showers from photon-like electromagnetic showers. Moreover, the dominant background in the MiniBooNE analysis, neutral current π^0 production, can be extremely reduced using the powerful imaging techniques of a LArTPC. The analysis techniques developed for the low energy excess search will be developed in the common software framework known as LArSoft. This software framework is common amongst many of the LArTPC experiments, helping ensure that the reconstruction techniques and analysis strategies developed on MicroBooNE will have applicability to future experiments.

MicroBooNE will also be able to measure many high-statistic cross-sections at $E_{\nu} < 1$GeV. At this energy range, the impact of various nuclear effects such as final state interactions and short-range nucleon correlation are poorly understood. These nuclear effects can change the classification of neutrino nucleus interaction, and thus change the measured cross-section. The fine grain tracking offered by LArTPCs allows for the classification of neutrino-nucleon interaction in terms of final state particles instead of using simplifications such as the quasi-elastic scattering assumption. Moreover, with a proton threshold measured as low as 21 MeV of kinetic energy [**?**], these nuclear effects can event be measured with high statistics using neutrinos as a probe. The broader neutrino cross-section community is anticipating how the results measured by MicroBooNE compare to previous measurements.

11.1 MicroBooNE Operations

UT Arlington group will continue to play a major role in the data taking and operations of the MicroBooNE detector. PI Asaadi has served as the TPC commissioning leader and now as the TPC operations expert. Asaadi has only recently stepped down as Astro-Particle and Exotics working group convener, but remains active in this group for the foreseeable future where a natural synergy exists within the UTA group given PI Yu's role as BSM convener on DUNE. MicroBooNE will explore the physics capabilities of LArTPC including classification of low energy events as a background for supernova neutrinos and searching for cosmogenic backgrounds related to proton decay analysis.

One post-doctoral researcher supported by this proposal will part of their time working on the MicroBooNE operations and is expected to be trained to serve as the TPC operations expert. This is in addition to the effort expected to be present from the postdoc supported by startup funds in the first two years of the proposal. In addition to data taking shift requirements, the he/she is also expected to play a role in the online DAQ/data quality management as training for the future planned work on the SBND DAQ. With MicroBooNE just finishing the commissioning of their continuous readout data stream ("supernova data stream"), UTA hopes to play a role in supporting the analysis and improvement of this system. The graduate student supported by this work is also expected to take shifts on MicroBooNE and play a supporting role on the expert training.

11.2 MicroBooNE Data Analysis

Being a driving force on early neutrino cross-section analysis is a good way to have impact on the physics program at MicroBooNE. The postdoctoral researcher and graduate student are expected to work on neutrino cross-section analysis using the data taken in the first years of running in addition to measurements done once the full SBN program is operational. This data set will provide many first glimpses into the short-baseline analysis. Following up on previous low statistics cross-sections measured by ArgoNeuT is one way which the UTA can have immediate impact and leverage our previous experience where Asaadi played a major role.

An example of one such cross-section measurement that is of immediate interest, shown in Figure **??**, is the charged current coherent charged pion production (CC Coh-π). This result is of particular interest because it is an example of a relatively simple topology, but one where theory and experiment do not agree. Previous attempts to measure this cross-section at low energy by the SciBooNE and K2K collaborations have proven unsuccessful. However, the analogous neutral current process (NC Coh-π^0)has been observed at low energy. To further complicate the picture, two higher energy measurements from ArgoNeuT and Minerva both show observation of CC Coh-π although somewhat at odds with various modern neutrino generator predictions. The initial MicroBooNE data set will be a valuable tool in disentangling this and many other cross-section oddities and allow for a better construction of ν-Ar scattering models.

The tools developed for data analysis and reconstruction in MicroBooNE will have transferability to the other SBN LArTPC experiments through the use of the common software package, LArSoft. The UTA group has developed a good deal of expertise with this software package and will continue to contribute to its development as a tool to perform a synthesized analysis across the SBN.

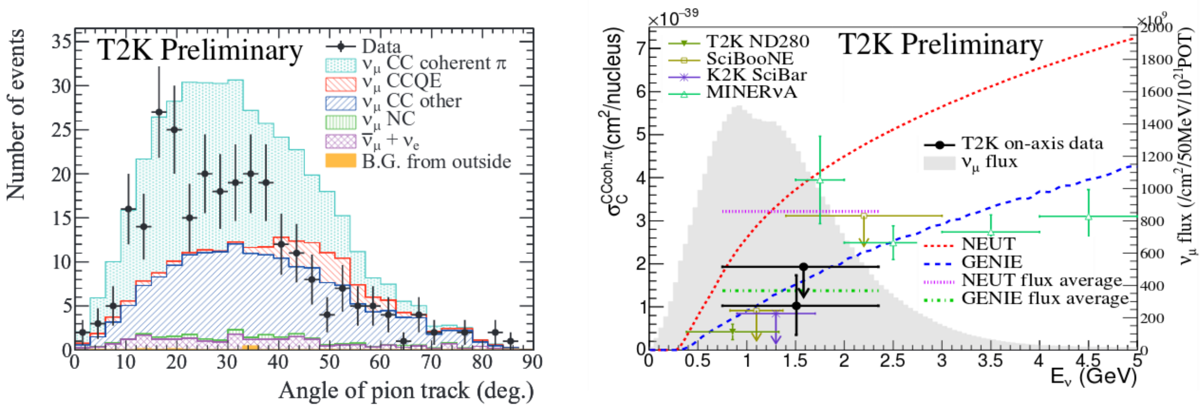


Figure 16: Recent results from T2K [] showing the tension which exists from the low-energy and high energy measurements of the charged-current coherent π production. With the SciBooNE and K2K experiments showing no evidence of this process at $E_\nu < 1$ GeV but ArgoNeuT and Minerva both measuring this process at higher energy. Moreover, the recent results from T2K disagree with the current cross-section models.

12 ICARUS Experiment (PI: Asaadi, Yu)

The ICARUS-T600 detector is the largest LArTPC experiment ever actualized containing 760 tons of purified liquid argon (476 tons of active mass). Comprised of two 300 ton modules, the T600 detector initially tested in Pavia, Italy in 2001 where one of the two modules was exposed to surface running for a three month period. Extensive system testing was performed before the complete system was transported to the underground Gran Sasso National Laboratories (LNGS). In 2010, the entire T600 detector was brought online at Gran Sasso where it completed a three year neutrino run in the Cern to Gran Sasso (CNGS) neutrino beam corresponding to 8.6×10^{19} protons-on-target. The successful operation of a large LArTPC experiment in an underground facility with $> 90\%$ data taking efficiency (collecting $\sim$3000 neutrino events) and achieving high argon purity and long argon lifetime represents a major technological milestone for LArTPC's.

In 2014 the ICARUS-T600 detector was decommissioned and transported to CERN to undergo a refurbishment and upgrade in anticipation of its future non-underground operation at Fermilab's SBN program. Figure **??** shows one of the two TPC modules at CERN undergoing refurbishment. Each module in the ICARUS detector is comprised of a common cathode and a TPC with dimensions 18.0 m $\times$ 1.5 m $\times$3.2 m (l$\times$w$\times$h). The TPC has three instrumented wire planes with the first two induction planes oriented at $\pm 60°$ to the beam axis and the final plane oriented horizontally. Both the pitch and wire spacing is chosen to be 3 mm which provides superb resolution for imaging interactions inside the detector.

The importance of the ICARUS-T600 experiment to the experimental reach of the SBN program is shown in Figure **??**. Plotted is the significance with which an experimental configuration covers the 99% confidence level (C.L.) for the allowed sterile neutrino mixing from the LSND experiment as a function of Δm^2 (the mass difference between the active and sterile neutrinos) for the simplest 3+1 model. The gray bands represent ranges of Δm^2 where LSND reports no allowed regions at 99% C.L. The presence of the ICARUS-T600, by providing a large sensitive mass at the far detector location, is absolutely imperative for the SBN program to achieve a definitive (5σ) coverage of the LSND allowed region.

The UTA group has already begun contributing to the ICARUS experiment with the continued

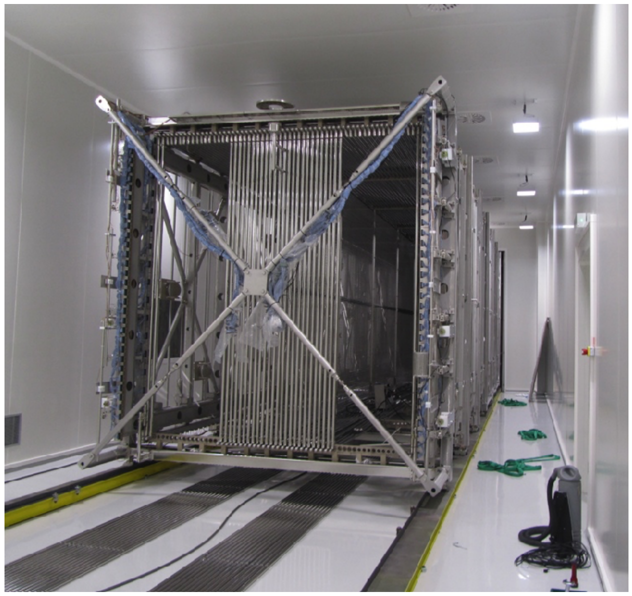


Figure 17: An ICARUS TPC module located at CERN undergoing refurbishment in anticipation of the move to Fermilab in 2017-2018.

stationing of the post-doctoral researcher Andrea Falcone at CERN to continue his contributions to the upgrade of the ICARUS light detection system. The upgraded light detection system is currently being installed with 90-PMTs per TPC providing an estimated 5% photo-cathode coverage. The increased coverage will allow for excellent trigger efficiency for neutrino induced events as well as providing cosmogenic background rejection. Falcone is also leading the work to develop the readout electronics for the light detection system and integrating them into the common data aquisition system (artDAQ) used by the other two SBN experiments.

12.1 Installation, and Commissioning

By participating in both the installation, commissioning, and data taking of the SBND and MicroBooNE as well as leveraging on the experience of Dr. Falcone's work on ICARUS, the researchers supported by this proposal will be well positioned to contribute to the installation, commissioning, and first data analysis of the ICARUS LArTPC upon its arrival at Fermilab. Having a robust team of researchers based at Fermilab to provide expertise and support for the ICARUS system will ensure the successful execution of the SBN program.

Falcone is expected to travel with the ICARUS detector when it moves to Fermilab in early 2017 and play a key role in the commissioning and data acquisition of the light system. At the same time he will be training the other post-doctoral and graduate researchers on the ICARUS system to ensure a smooth first data taking in mid to late 2017. These detector experts are expected to remain in residence at FNAL during the initial operations of the detector and play a key role in early data analysis.

12.2 ICARUS Data Analysis

In addition to providing the necessary sensitivity in the $\nu_\mu \to \nu_e$ oscillation channel, the large mass and long length of the detector allow for more complete containment of high energy muons

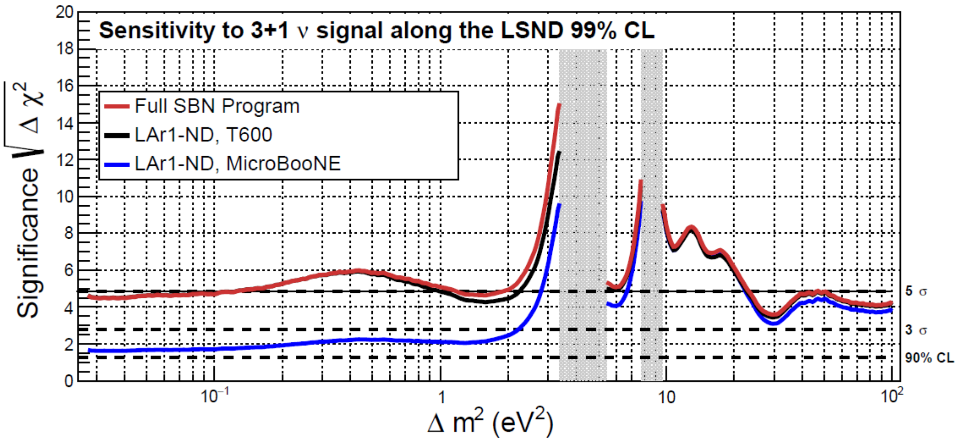


Figure 18: The experimental sensitivity for $\nu_\mu \to \nu_e$ oscillations including backgrounds and systematics assuming a nominal three year exposure in the BNB for the SBND and ICARUS experiments and a six year exposure for the MicroBooNE experiment.

and electromagnetic showers due to $\pi^0 \to \gamma\gamma$ decays. Using this, and the deployment of a near detector in the BNB beamline, a complimentary sterile neutrino search looking for muon neutrino disappearance as well as neutral current disappearance becomes possible. The extended length of the ICARUS-T600 detector provides better π/μ separation (since pions have a higher cross-section to interact) as well as more accurate muon energy reconstruction (since more muons will be fully contained) thus extending the sensitivity in the muon disappearance channel.

Similarly, by targeting a clearly identifiable neutral current process (such as NCπ^0 production) the disappearance rate can be measured at both the near and far detector to search for the sterile neutrino signature in a complimentary way to the ν_e appearance. ICARUS's large volume ensures near complete photon shower containment and thus increases the statistics available for a NCπ^0 disappearance search.

On top of the three detector SBN program, the stand-alone T600 detector can offer physics insight through the study of neutrino cross-sections at energies pertinent to the future planned Deep Underground Neutrino Detector (DUNE). The ICARUS experiment can due this because it will see a significant off-axis component of the Neutrinos from the Main Injector (NuMI) beam. The NuMI beam uses 120 GeV protons to produce a higher energy neutrino beam than the BNB. ICARUS is expected to collect one neutrino event every 150 seconds from the NuMI beam in the energy range of 0-3 GeV. Such high energy neutrino cross-section data on an argon target will provide valuable input to the DUNE experiment and offer experimental measurements of detector efficiencies and event reconstruction techniques at these higher energies.

Part IV

The Fermilab Long-Baseline Neutrino Program

The Deep Underground Neutrino Experiment (DUNE) [**?**] aims to utilize massive LArTPC's to measure the CP phase in the neutrino sector as well as determine the neutrino mass hierarchy. DUNE will use a high power wide band beam capable of producing neutrinos and antineutrinos directed from Fermi National Accelerator Laboratory (FNAL) outside of Chicago, Illinois towards massive underground LArTPC detectors located in the Sanford Underground Research Facility (SURF) 1300 km away in Lead, South Dakota. By measuring the asymmetry between appearance of electron neutrinos from a beam of muon neutrinos ($P(\nu_\mu \to \nu_e)$) compared to the appearance of electron antineutrinos from a beam of muon antineutrinos and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$) as well as the precise measurement of the ν_e energy spectrum measured at the far detector, a measurement both the CP violating phase and the mass hierarchy can be done in the same experiment. In order to achieve this measurement, DUNE will require three essential components:

1) High power neutrino beam:

   A neutrino beamline designed to provide sufficient intensity and appropriate energy range to exaggerate the sensitivity to the first and second oscillation maximum. The beam comes from a conventional, horn-focused neutrino beamline generated from 60 GeV - 120 GeV protons from the Fermilab Main Injector designed for initial operation at proton-beam power of 1.2 MW, with the capability to support an upgrade to 2.4 MW. The beam shall be sign-selected to provide separate neutrino and antineutrino beams with high purity to enable measurement of CP violation, the neutrino mass hierarchy, and precision oscillation measurements.

2) Large mass underground far detector:

   The far detector is designed to be a 40 kiloton LArTPC consisting of four 10 kT detectors. These detectors are to be deployed 4850 feet below the surface in caverns located at SURF in order to reduce the number of cosmic rays in time with the neutrino beam to $\sim 1\%$ of the expected background. These detectors are capable of precision $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ identification and energy measurements to provide definitive measurement of the CP-phase and mass hierarchy.

2) Precision near detector:

   The near detector, which is exposed to an intense flux of neutrinos, also enables a wealth of fundamental neutrino interaction measurements. The current reference design for the DUNE near detector includes a NOMAD-inspired [**?**] fine-grained tracker consisting of a 3.5 m$\times$3.5 m$\times$6.4 m; central straw-tube tracker, a lead-scintillator sampling electromagnetic calorimeter, a 4.5 m$\times$4.5 m$\times$8.0 m large-bore warm dipole magnet surrounding the straw tube tracker and calorimeter providing a magnetic field of 0.4 T, and RPC-based muon detectors located in the steel of the magnet as well as upstream and downstream of the tracker.

13 Deep Underground Neutrino Experiment (DUNE) (PI: Asaadi, Yu)

We describe in detail the project listed in the strategic plans. The primary goal of the projects listed in this section are to ensure the group to play leadership role in construction of first two 10 kt modules of DUNE as well as in physics topics of the group's interests.

13.0.1 Beyond the Standard Model physics group leadership - Yu

In addition to the standard neutrino physics topics, neutrino mass hierarchy and CP violation measurements in the neutrino sector, the expected high intensity proton beams provides ample opportunities for DUNE to look for physical phenomena beyond the Standard Model. Thanks to the consistent efforts of Yu's and other members within the DUNE collaboration, the beyond the

Standard Model physics group has been created at the collaboration meeting in Sept. 2015 with Yu as the convener. Yu quickly organized the group into five subgroups based on primary physics interests and to provide necessary simulation and analysis tools specialized to support the BSM group physics analysis. The five subgroups are the simulation and software group led by our postdoctoral fellow, Chatterjee and four physics topics what cover Low Mass Dark Matter search (LDM), the Sterile Neutrino Search, the Non-standard Neutrino Interactions and Heavy Neutrino searches. Additional physics topics would continued to be added to the group's interest but these four physics topics are the primary topics to be studied in the coming 1.5 to 2 year time scale with the goal to provide the results for DUNE Technical Design Report (TDR) scheduled to compelte by summary 2019. In preparation for TRD, the group plans on producing the write up for the initial list of topics and tasks to complete to provide sensitivity studies for TDR, along with the milestones for the group to follow. We anticipate that the list of tasks will be essential for the new members to participate in BSM group's planned studies.

13.0.2 Beam Simulation Tasks for LBNF

UTA group has contributed to beam simulations for optimization and systematic studies of the Long Baseline Neutrino Facility (LBNF). All new students joining the group are required to learn root and beam simulations as part of their training process. Since most of these tasks are well defined, each student can be assigned to the given task until they complete the task and write up the report. Many undergraduate students were able to make helpful contributions in these tasks and made presentations at beam simulation group meetings for tangible contributions. We plan on continue contributing to the beam simulation group's tasks for various studies, including an improved decay pipe radius dependence of the CPV sensitivity, target dimenstion and material dependence of neutrino flux and magnetic field map computations and display. New students will be assigned of additional tasks that are helpful for beam optimization group based on the discussion with the leadership of the group. This will allow students to continue improving their analysis skills while working on hardware projects.

13.1 APA QA/QC

Given that the highest priority of DUNE is to establish and demonstrate the functionality of its baseline technology, namely the single phase LArTPC, Asaadi will be focusing on the quality assurance, quality control, and commissioning of the anode plane assemblies (APA's) for protoDUNE SP. This work will help building up infrastructure, expertise, and capabilities necessary to contribute and lead in the DUNE SP far detector construction.

13.2 Field Cage for protoDUNE Dual Phase

Field cages provide uniform electric fields for ionization electrons to drift to anodes for the detection in the Time Projection Chamber. The baseline design for DUNE LArTPC is that of the single phase in which the ionization electrons created by the secondary particles resulting in neutrino-nucleon interactions drift in LAr and get detected on the anode plane that resides inside the liquid phase of argon. An alternative technology is the LArTPC that the ionization electrons drift through LAr but then extracted through the strong extraction field at the top of the liquid and detected in the anode in gaseous phase of argon after a signal amplification via an large area gas electron multiplier (LEM), hence the dual phase.

During the period of his sabbatical stay at CERN, Yu has begun to work on WA105, a dual phase $6m \times 6m \times 6m$ prototype testing project at CERN through the participation in the smaller prototype cosmic ray detector in $1m \times 1m \times 3m$. This work provided an opportunity for UTA IF group to join WA105 as the first U.S. group and to position itself well to play a leading role in dual phase. While dual phase technology is currently at a lower priority to the single phase LAr TPC, it is clear that U.S. groups' participation in alternate technology is beneficial in many perspectives, including that of strengthening the international nature of DUNE collaboration an essential ingredient in its success.

As the schedule for DUNE experiment and for the two protoDUNE experiments get clearer, it became apparent that UTA will be able to play an importnat role in design and construction of these experiments. The overarching strategy in identifying the construction was to ensure UTA's contribution to any of the two protoDUNE experiment would aim to direct participation in DUNE from the first 10kt module in early 2020s. One such component easily identifiable is the field cage for which the collaboration is targeting to utilize as much common components as possible for single phase and dual phase protoDUNE detectors. With this premise, Yu has discussed with the DUNE management and has agreed to take the responsibility in design and construciton of dual phase field cage together with the University of Zurich group.

Figure **??** shows the current conceptual design of the field cage for the dual phase protoDUNE experiment. The primay concept of this field cage is to use compartmentalized structure of submodules that consist of several straight profiles to provide voltage differentials for the generation of uniform fields. The use of straight profiles made of either aluminium or stainless steel makes the preassembly and shipment of submodules convenient. Each of these submodules will be prepared to the quality to hold high voltages at 180kV (for single phase) or 360kV (for dual phase) over the drift length.

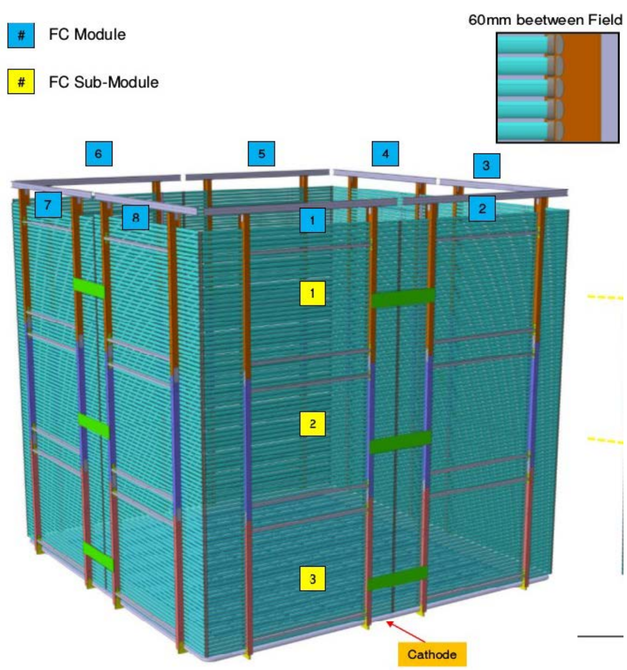


Figure 19: Conceptual skematic drwaing of the field cage assembly for dual phase protoDUNE.

At present, it has been agreed that either CERN or Fermilab will be responsible for purchasing and production of the necessary mechanical parts, including the I–beams that act as the spine of the submodule and the each profile. The project funds will pay for the purchase electrical parts - voltage divider resisters and varistors for surge arresting - and the production of electronic boards the field cage. UTA will work with the single phase field cage group, including BNL team, and the single phase field cage electronics group at Louisiana State University as well as the University of Zurich group on design of both the mechanical and electrical part of the dual phase field cage. We will be responsible for pre-assembly of the field cage submodules, mounting of the electric boards, testing of each submodules and performing functional prototype testing with as large a field cage as possible before shipping the dissembled submodules out to CERN for installation.

For the completion of the design of the dual phase field cage, our postdoctoral fellow, Animesh Chatterjee will be stationed at CERN starting from October 2016 through mid January 2017. During this period, Chatterjee will work with the ETH and CERN groups to finalize both mechanical and electrical design of the field cage for dual phase protoDUNE and ensure as much a commonality as possible with that of the single phase. Once these design parameters are agreed with the single phase field cage groups, a production could proceed. The parts for the dual phase field cage will be shipped to UTA for the clean up and preparation of each of the parts, assembly of submodules, mounting of electrical components, and electrical and mechanical testing for a submodule qualification. A sizeable functional prototype field cage of size $6m \times 6m$, an electrically independent unit, will be put together and be subject under high voltage, though it may not be as high as 360kV given that the testing will be performed in air. Once the functional testing completes, the functional prototype will be disassembled and shipped to CERN for the installation.

Since protoDUNE time scale has a hard limit of completing the beam data taking before CERN shutdown in 2018, it is essential for our group to operate under this time restriction in mind as presented in the strategic plan in section **??**. To meet these goals, Yu plans on staying out at CERN in fall 2017, thanks to the remaining funds from the agreements with LAPP and ETH which covers costs for local stay at CERN and the teaching buyout. A UTA postdoctoral fellow will also be stationed out at CERN together with a graduate student to help with both single and dual phase protoDUNE installation and commissioning. Yu will then return to the U.S. at the end of year 2017 and Asaadi will be stationed out at CERN for the first half of 2018 to continue fulfilling our responsibilities in both the protoDUNE experiments.

At the time of writing this renewal proposal, the dual phase protoDUNE field cage group is working closely with the group for the single phase to agree on common design parameter for mechnical and electrical components of the field cages, such as the dimension of each profile bars of the field cage, the material, the electrical board design, quality and tolerance of resisters and varistors, etc.

Part V
Research in Detector R& D

PI Summary: David Nygren

PI Summary: Benjamin Jones

SiPMWheel: a large-area, position-sensitive, energy-resolving light collector (Asaadi, Jones and Nygren.)

14 Introduction

The designs of scintillation light collection systems for noble element time projection chambers (TPCs) are driven by two main requirements:

- Photons with very short wavelengths (128 nm in Ar, 175 nm in Xe) must be collected.
- Large surface areas must be instrumented to collect as much light as possible, with a channel count kept low in order not to drive up the system cost.

Although some VUV-sensitive light detectors are available [?, ?], their quantum efficiency at these wavelengths is typically not high, and their surface area per channel is not large. To sensitize visible light detectors to VUV photons a wavelength shifter is often employed, absorbing in the UV and emitting in the visible. A common choice is tetra-phenyl butadiene (TPB) [?, ?, ?, ?, ?, ?, ?]. A fraction of the visible light thus emitted can then be detected by a standard photon detector like a silicon photomultiplier (SiPM) or a photomultiplier tube (PMT). Several geometries have been considered, including through-plate systems [?, ?], high-reflectivity foils [?, ?], and light-guides [?, ?, ?]. Light guide systems, have the advantage that large areas can be sensitized with only a moderate channel count. However, it has the disadvantage that light losses through non totally-internally-reflected rays, and surface scattering and re-absorption effects [?] are significant, and that the collection efficiency depends on the geometrical position of light arrival, making calorimetric reconstruction of localized events difficult.

We propose to develop a new large-area wavelength-shifting detector based on the light-guiding concept, with significantly improved collection efficiency and calorimetric performance. This concept is motivated by the needs of the NEXT neutrinoless double beta decay experiment [?] and by low energy physics analyses such as those of supernova neutrinos, proton decay and solar neutrinos in large liquid argon TPC detectors like DUNE [?, ?]. The pervasiveness of noble-element TPCs in particle physics is so widespread that light collection solutions with strong position and / or strong calorimetric resolution potential are likely to be widely applicable. Use cases as a primary scintillation detector may include noble element dark matter searches and other surface and underground liquid argon TPC detectors, and as an electroluminescent energy plane may include the DUNE two-phase far detector and possible argon gas near detector.

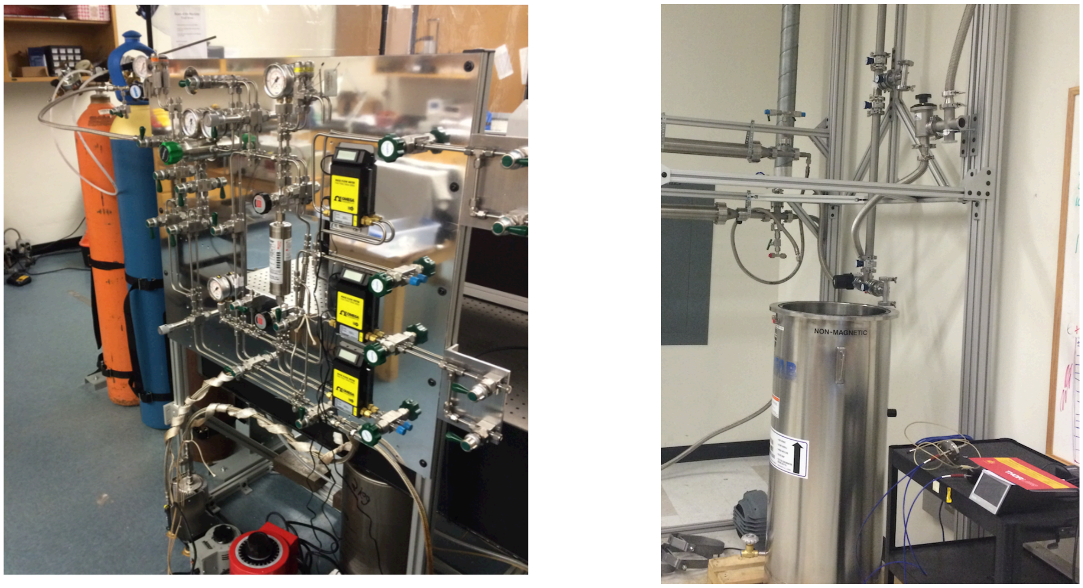


Figure 20: Left: Existing high pressure xenon gas purification and recirculation system in the lab of Nygren and Jones. Right: Existing liquid argon purification system in lab of Asaadi.

15 Research team, existing facilities, and details of request

This project will be led by Profs. Jonathan Asaadi, Ben Jones, and David Nygren at UTA. It will make use of existing liquid argon and high pressure xenon gas purification systems which are already operational at UTA and shown in Figure **??**.

This project also leverages the experience of these researchers. Nygren is the inventor of the time projection chamber [**?**] and a pioneer of electroluminescent xenon detectors for neutrinoless double beta decay [**?**, **?**, **?**, **?**, **?**, **?**]. He is spokesperson of the NEXT collaboration and developed a test stand that demonstrated energy resolution near the intrinsic limit of xenon gas [**?**] (1% FWHM at 662 keV), the worlds most precise energy resolution from a xenon detector. Asaadi is a prominent member of the MicroBooNE [**?**], SBND [**?**], DUNE [**?**] and LArIAT [**?**] collaborations, with expertise in liquid argon TPC detector design, development and construction [**?**]. Jones has extensive experience in noble element light collection, including the developing "Wunderbar" light-guide detectors for large LArTPCs [**?**, **?**, **?**]; assembling and operating the Bo liquid argon optical test stand at Fermilab [**?**, **?**, **?**]; exploring wavelength shifter properties and photochemistry [**?**]; and simulating light in liquid argon [**?**, **?**].

Most supporting equipment for this project is already available or will be purchased from University funds, including the test stands, data acquisition systems and SiPMs, all of which were already acquired for other projects. To pursue this research we request support for:

1. Personnel: one FTE graduate student (in the form of two students at 50% effort level each), and one undergraduate.

2. M&S costs: to include argon and xenon supply, as well as fluors and plate materials.

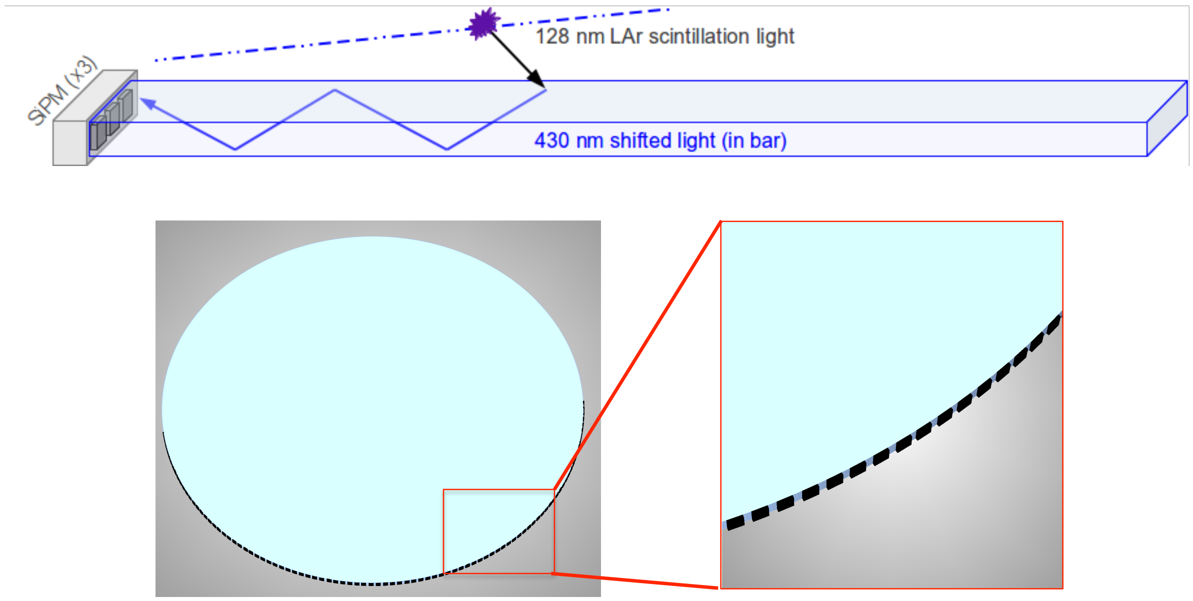


Figure 21: Top: Example of operation of bar detectors, like the “Wunderbar” - image from [?]. Bottom: Drawing of plate detector we propose to develop.

16 Detection concept and comparison to existing devices

The detector we plan to develop will use an array of silicon photomultipliers (SiPMs) coupled around the perimeter of a TPB coated plate. As with bar-type light-guide detectors (hereafter referred to as “bars”), shown in Figure **??**, top, VUV photons absorbed at the coating surface are re-emitted in the blue, some of them into the totally internally reflected modes of the polymer plate. In contrast to bar detectors, the SiPMWheel is instrumented at many points around the perimeter. This provides significant advantages which we hope to demonstrate: 1) the sensitive surface area is maximized relative to the allowed path-length between emission and detection, which optimizes light collection efficiency against losses during propagation; 2) the fraction of solid angle outside the totally internally reflected range is much reduced, leading to a higher trapped light yield 3) by reading out all SiPMs, geometrical information about the event can be extracted - as well as being intrinsically useful, this position information allows for a correction to be applied to improve calorimetric response.

In this section we derive some quantitative comparisons between our proposed SiPMWheel detector and the more typical bar-type geometry. We assume the same coating properties can be achieved over a 2D surface for both plates and bars (fabrication of the “Wunderbar” is easily generalizable [?]) and that the bar length / plate radius are free parameters to be optimized for each device.

When comparing different light collection technologies it is important to define a useful Figure of merit (FOM). The following FOMs, though by no means exclusive, appear to represent reasonable ways to assess the light collector performances for our intended use cases:

1. For illumination by a distant light source, how many photons can be captured per SiPM?
2. For illumination by a distant light source, how many photons can be captured per detection unit (one plate or one bar with many coupled SiPMs)?

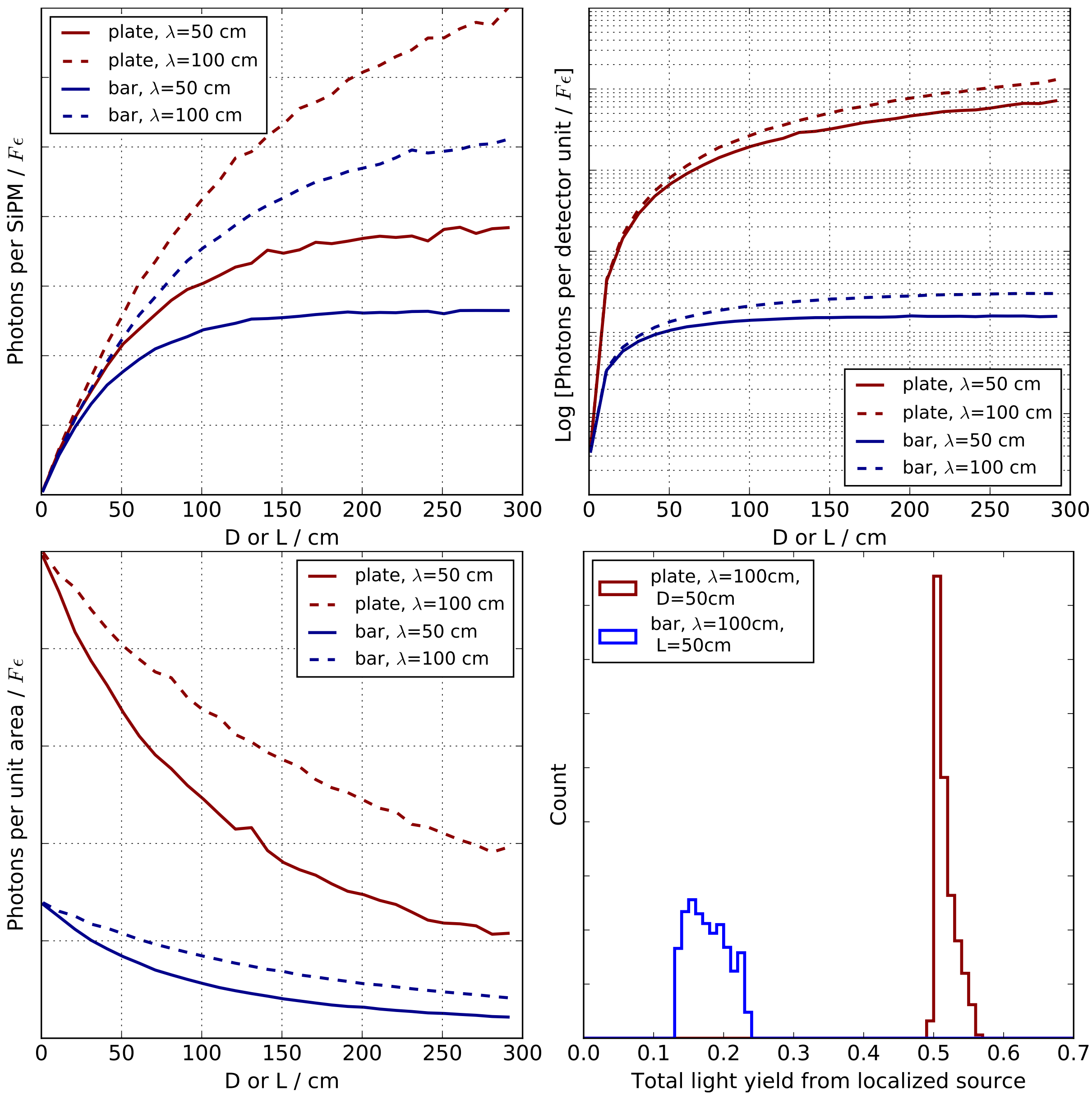


Figure 22: Comparison of plate-type to bar-type detectors with various figures of merit described in the text. The plate significantly outperforms the bar-type detector in all cases. Top left: photons per SiPM. Top right: Photons per detector unit. Bottom left: Photons per unit area. Bottom right: total yield and spread from localized mono-energetic sources.

3. For illumination by a distant light source, how many photons can be captured per unit surface area?

4. For localized light deposits at different positions, what is the collection efficiency and how uniform is it?

The parameters of the detector geometry may be optimized differently to satisfy each criterion for both bar and SiPMWheel detectors. As simplifying assumptions we assume that the thickness of the plastic sheet used to make both the bar and plate is equal to the SiPM width, which we take to be 5mm. We assume both can be prepared with the same coating quantum efficiency ϵ, are cut from the same material (acrylic with refractive index n=1.5), and that attenuation in the light guide is exponential in light-ray length parallel to the coated surface (this is known to be invalid at very short distances but is a reasonable approximation for longer path lengths [**?**]). We consider two values of the parallel attenuation length λ that appear reasonable based on past studies, $\lambda = 50$ cm and $\lambda = 100$ cm [**?**, **?**]. Finally we assume that the 5 mm SiPMs are placed with 5 mm spacing between each, which gives three SiPMs per bar, or as many as can fit around the radius of the plate detector. The FOMs above are compared using the output of a simple ray tracing simulation.

FOM (1) is compared in Figure **??**, top left. For both detector types, the collection efficiency increases as the device becomes larger, saturating at a distance comparable to the attenuation length, as expected. The plate-type detector has consistently higher collection efficiency and a higher saturated value. This is primarily due to the loss of supercritical rays in the bar detector, which the plate detector does not suffer from.

Whether the most useful Figure of merit is the light yield per channel or the light yield per detector unit depends on which factor is limiting in the experimental design or budget. A moderate improvement in FOM (1) corresponds to an enormous improvement in FOM (2) because each plate detector has a large number of SiPM channels, whereas each light guide detector has only 3. This comparison is shown in Figure **??**, top right (note log scale). The improvement in FOM (3), the light collected per unit area, is intermediate between these two cases, and is shown in Figure **??**, lower left. In all cases, our proposed detector represents a major improvement.

FOM (4), the stability of the light yield for light at different locations, is quantified in Figure **??**, lower right, which shows example total light yield distributions for localized deposits in random positions across a device with 50 cm length / diameter and 100 cm attenuation length. Note that no photon counting fluctuations are included in these distributions - they show only the changing light yield due to differences in the detector response in different locations. Though much improved over the bar-type detector, the energy resolution obtained by simply integrating photons is still not sufficient for sub-% precision calorimetry. However, the light yield is correlated with the light source position, which in the case of the SiPMWheel, can be extracted from the distribution of light between SiPMs. The position resolution and hence the quality of the correction depend strongly on the number of photons detected, and will vary between applications, improving into the sub-percent regime as the detected photon count becomes increasingly large. The quality of this correction and the optimal method for applying it is something we plan to explore in both simulation- and hardware-based studies if this proposal is funded.

17 Electroluminescent TPC use case: The NEXT Experiment

The NEXT collaboration is a primarily US-European collaboration with the goal of developing a ton-scale, ultra-low-background neutrinoless double beta decay detector using high pressure ^{136}Xe gas (GXe) as the active medium. This technology has energy resolution far surpassing other xenon-based detectors, and a reconstructable topological signature for neutrinoless double beta decay events which is absent in liquid xenon (LXe) or xenon-doped liquid scintillator (LSXe). The projected background indices, which will ultimately limit experimental sensitivity at the ton scale, are 9 counts per ton per year per ROI (ctyR) for GXe, 130 ctyR for LXe and 210 ctyR for LSXe, as assessed by an independent review [**?**].

The NEXT detector is based on an electroluminescent TPC concept. Ionization charge is drifted towards a high-field region where it is amplified through nearly fluctuation-less electroluminescent gain. Each electron is accelerated in the field of the amplification region, creating

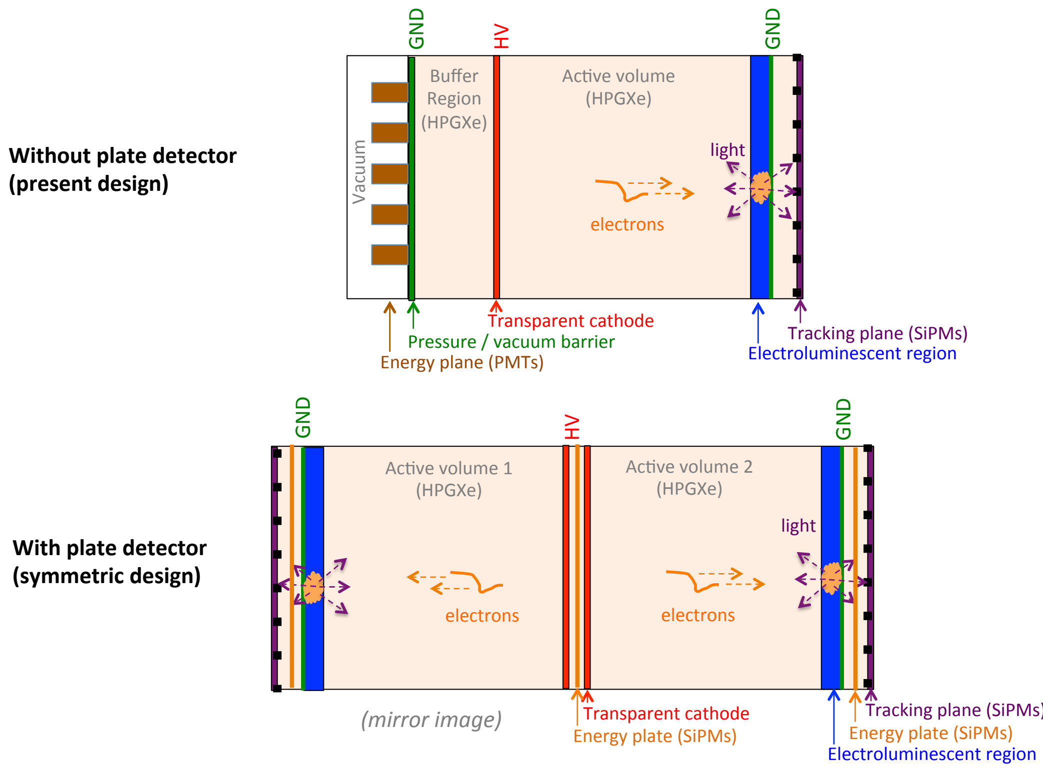


Figure 23: Left: Existing asymmetric TPC design, where energy must be recorded using the PMT-based "energy plane". Right: Symmetric design that could be realized using a high-resolution "plate detector". Plate detectors may be deployed at the anode region, the cathode region, or both.

excited xenon atoms which decay radiatively, emitting 175 nm light. This light is collected by two subsystems. Directly behind the electroluminescent region is a tracking array of SiPMs on a 1 cm grid. These record an image of the amplified event and allow for event topological reconstruction. Their placement is sufficiently sparse that the integrated light yield per MeV depends on the precise geometry of the event too strongly to provide a calorimetric measurement with the required precision of $\sim$1% FWHM - this is shown schematically in Figure **??**, top left. Addition of more SiPMs to give a complete tiling is possible but costly. Even if this were implemented, the dark rate of the many SiPMs would like produce fluctuations in the measured energy that prevent intrinsic resolution from being achieved.

To circumvent this limitation, in the present generation of the NEXT detector, the calorimetric reconstruction of the event is handled by a different subsystem consisting of low-radioactivity PMTs at the cathode end. Light emitted in the electroluminescent region is reflected around the detector by PTFE foils and shifted to the blue by TPB coatings, and detected by the PMTs of the"energy plane". With this arrangement, energy resolutions corresponding to 0.63% FWHM at $Q_{\beta\beta}$ have been demonstrated [**?**]. A sketch is shown in Figure **??**, top.

This two-plane solution is not without drawbacks. Even the low radioactive photomultiplier tubes represent a significant fraction of NEXT-100's radioactivity budget, contributing approximately 0.4 counts per ton per keV per year in each of bismuth at thallium backgrounds at $Q_{\beta\beta}$, representing the largest absolutely measured background contribution. The PMTs must be operated outside of the high-pressure region which introduces an engineering challenge, requiring an evacuated volume to be optically coupled to the active region at 15 bar. Finally, the PMTs must be

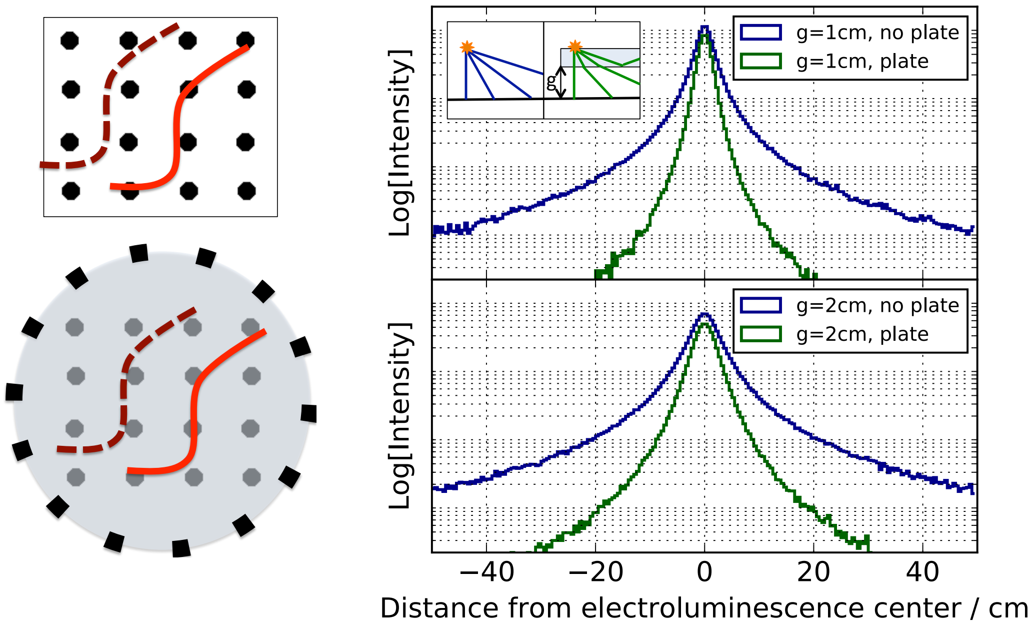


Figure 24: Left: Track energy measurement with tracking plane only (top), and tracking plane + plate (bottom). Right: Focussing effect of plate on transmitted electrolumiscence light, which may improve tracking resolution in NEXT.

operated in a low-field region which leads to the HV being graded down in a short "buffer region", wasting valuable xenon mass and introducing a region of larger HV stress.

A highly efficient calorimetric plate detector as we have described would allow a significant improvement to the NEXT design. Instead of measuring energy at the cathode, a wavelength-shifting plate between the electroluminescent mesh and the tracking plane could be used to integrate light emission from the mesh. Since the plate has a uniform collection surface, dependencies of the light yield on event geometry does not spoil its resolution, as shown in Figure **??**, bottom left. The light which is not guided into the plate escapes through the back surface to be used for tracking. The plate also provides a focussing effect shown in Figure , right, removing high-angle rays from electroluminescence and potentially improving the tracking resolution of the detector. It is also plausible to add another energy plane detector behind the cathode transparent cathode. This adds the electrical complications of SiPMs being operated at high voltage, but increases the calorimetric area by a factor of two. Finally, because the vacuum region and buffer region are no longer necessary, this design allows a symmetric TPC to be realized, using the GXe volume in a highly efficient way and simplifying the delivery of HV. This concept is shown in Figure **??**, bottom.

18 Single-phase LArTPC use case: DUNE

Light collection in surface-based TPCs plays a critical role of identification of cosmogenic backgrounds which would swamp true neutrino events in the absence of an optical trigger [**?**]. In deep underground detectors like DUNE, where cosmogenic backgrounds are much reduced, the main goal of light collection systems is fundamentally different. Rather than being primarily a tool to reject energetic off-beam cosmic ray events, the light collection system allows extension of the physics program to low energy, non-beam physics.

The importance of light collection for non-beam physics is primarily related to establishing the position of the event in the drift direction. This is vital in order to apply a lifetime correction and thus obtain a well calibrated energy for the event from the TPC. Most of the off-beam neutrino physics goals of DUNE rely on energy reconstruction, either to identify the signal events or to learn about the physics of their sources.

The following are cases where a sensitive light collection system is vital for achieving the physics goals of DUNE:

- *Detection of supernova neutrinos* [**?**]. A high efficiency for detecting 5 MeV electrons has been cited as the detector goal for adequately performing this physics. This is to be contrasted to the design goal of the MicroBooNE optical system, the largest running LArTPC optical system in the USA, which was to efficiently trigger on 40 MeV protons across the (much smaller) fiducial volume. Clearly, to meet DUNE's ambitious off-beam physics goals, high light-yield technologies surpassing existing systems are required.

- *Studies of solar neutrinos with DUNE* [**?**] have been discussed. This also requires sensitivity to few-MeV energy deposits across the fiducial volume, with the physics capability extending as the achievable trigger threshold is reduced. This physics will be greatly enhanced by any improvement in light collection efficiency.

- *Proton decay* [**?**]. Golden chanels for proton decay in DUNE include $p \to K^+\nu$, $p \to K^0\mu^+$ and $p \to K^+\mu^-\pi^+$. Detecting these modes requires not only to trigger on the off-beam events (likely not too challenging due to the large Q-value in the decays), but also identification of the kaon and muon daughters. Reliable identification is difficult with the TPC alone, since in many cases the "kink" in the outgoing track where the daughter particle decays is not strongly pronounced. It is thus of benefit to access the detailed time-structure of the event, and reconstruct the muon, and potentially even kaon events in time. A high collection efficiency with the optical system may allow this temporal reconstruction.

The present baseline design for the DUNE optical system is a system based on bar detectors. We have shown in Section **??** that the SiPMWheel is expected to improve upon the collection efficiency of similarly prepared bars when measured either per-SiPM, per-unit-area, or per-detector. The SiPMWheel also provides positional information - this will be valuable in cases where multiple events arrive within one drift window, as, for example, during the initial peak of flux from a nearby supernova. As with bars, the installation of SiPMWheels between mostly-transparent anode plane assemblies is possible as a deployment strategy. Two-side-coated as well as one-side-coated devices are also possible for this application.

19 Proposed program of work

The request in this proposal is primarily for personnel to develop this technology using already existing resources. We hope to acquire funding for two graduate students who will spend 50% of their research time for 3 years. The other 50% of each will be dedicate to analysis work and funded from other sources. One undergraduate will also support the team.

In the first year, development will focus on bench-top work, not involving noble element test stands. This includes learning to produce high quality optical coatings and testing them for efficiency and attenuation length in air, closely following and improving upon previous work with bar coatings (student 1, working primarily with Jones); and commissioning of a DAQ system capable of reading out large SiPM arrays and efficiently processing the data from these (student 2, working primarily with Asaadi). Possible improvements beyond the present state-of-the-art include the addition of coating stabilizing additives to improve fluorescence yield and the exploration of high refractive index polymers. Simulation topics relating to detector optimization and expected performance will be instigated as an undergraduate project in the first year. In the second year, bench-top experience will transition into noble element environments; with Nygren and Jones, one graduate student will build a subsystem as part of an existing high pressure xenon gas test stand whereby localized electroluminescent emission can be produced near the SiPMWheel surface at various positions to study its energy and position resolution. The other student will work with Asaadi to integrate the SiPMWheel detector with his planned liquid argon calibration test stand, where an independent program of work to deploy radioactive calibration sources in large liquid argon TPCs will already be underway. With these sources, the plate performance in liquid argon will be studied. The undergraduate will assist with one or both activities. The final year will involve a program of optimization of the detector, potentially along separate trajectories for use in LAr and GXe. At the end of the three year program we hope to have demonstrated strong energy- and position-reconstruction performance and suitability of the SiPMWheel as both an electroluminescence and primary scintillation light detector.

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19.1 EDUCATION AND TRAINING

- **Ph.D. in Experimental High Energy Physics, Westfield College, University of London (1969-1972)**
- **B.Sc (Honours) Physics, University of Southampton, U.K., (1965-1969)**

19.2 RESEARCH AND PROFESSIONAL EXPERIENCE

- **Professor of Physics, University of Texas at Arlington (1991-present)**
- **Research Scientist, High Energy Physics Group, University of Florida (1985-1991)**
- **Staff Physicist, High Energy Physics Group, Imperial College, University of London (1973-1985) (this included a period of work based at SLAC 1974-1976)**
- **Research Associate, HEP, Westfield College, University of London (1972-1973)**
- **Research Assistant, HEP, Westfield College, University of London (1969-1972)**

19.3 PUBLICATIONS:

1. ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ”, Phys. Lett. B 716 (2012) 1-29.
2. ATLAS and CMSCollaborations,“Search for invisible decays of a Higgs boson using vector-boson fusion in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”JHEP01 (2016) 172.
3. ATLAS and CMSCollaborations, “Search for Invisible Decays of the Higgs boson at the LHC”, A. White on behalf of the ATLAS and CMS Collaborations, Proceedings of LHCP 2015 Conference, St. Petersburg, Russia, August 2015
4. International Linear Collider, Technical Design Report, Volume 4, Detectors; http://www.linearcollider.org/ILC/Publications/Technical-Design-Report
5. “Experimental tests of particle flow calorimetry”, Felix Sefkow, Andy White, et al, Rev. Mod. Phys. 88, 015003 (2016)
6. ”Development of a Gas Electron Multiplier-based Digital Hadron Calorimeter”, A White et al 2012 J. Phys.: Conf. Ser. 404 01203

19.4 SYNERGISTIC ACTIVITIES

1. **D0 Intercryostat Detector:**: Invented the Intercryostat Detector for D0 used to correct the energies of particle/jets due to substantial losses in dead material.

2. **GEM-based Digital Hadron Calorimetry:**: Invented and developed the concept of Gas Electron Multiplier based digital calorimetry for high resolution jet energy measurements at colliders

3. **SiD Spokesperson:**: Spokesperson for the SiD Detector Concept for the International Linear Collider; leading and guiding all aspects of the concept towards its realization

4. **CALICE Collaboration:**: North American Representative for the CALICE Collaboration developing all aspects of calorimetry for future linear colliders.

5. **CERN RD51 Collaboration:**Deputy Chair and Member of the Management Board for RD51 - Micro-pattern Gas Detector Collaboration.

19.5 COLLABORATORS AND CO-EDITORS

- **ATLAS Experiment:** Ketevi Assamagan BNL, Joey Huston (MSU), Bill Quayle - U.Wits, Young Kee Kim - U.Chicago, Tae Hong - U.Pittsburgh, Elliot Lipeles - U. Penn., Alexander Madsen - DESY

- **SiD Detector Concept:** M.Breidenbach, J.Jaros, T. Barklow SLAC, M.Demarteau - ANL, H.Weerts ANL, J. Brau - U.Oregon, J.Strube - PNNL, M.Stanitzki (DESY)

- **CALICE Collaboration:** F.Sefkow - DESY, J.Repond - ANL, K.Kawagoe - Kyushu U.

- **RD51 Collaboration:** M. Hohlman - FIT

19.6 GRADUATE AND POSTDOCTORAL ADVISORS AND ADVISEES

1. **Mark Sosebee**, Ph.D., *University of Texas at Arlington,*

2. **Richard Bonde**, Ph.D., *University of Texas at Arlington*, **2015**

3. **Carlos Medina**, M.S., *Colorado School of Mines,***2010**

4. **Fajer Jafaari**, M.S., *University of Texas at Arlington and Tarrant County College,***2010**

1. **Dr. Seongtae Park**, Postdoctoral Fellow
   University of Texas at Arlington, **2010-2014.**

2. **Dr. Mark Sosebee**, Postdoctoral Fellow
   University of Texas at Arlington, **1996-present.**

Curriculum Vitae

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Education and Training

B.A./M.A., *Physics/Honors Curriculum*, *Summa Cum Laude*, Hunter College of CUNY, Class Rank 1/734	**1978-81**
Sc.M., *Physics*, Brown University	**1982**
Ph.D., *Physics*, Brown University	**1988**

Research and Professional Experience

Director, Center of Excellence in HEP, UT Arlington	**2011-**
Professor, University of Texas at Arlington	**2003-**
Associate Dean, Honors College, UT Arlington	**1999-2003**
Associate Professor, University of Texas at Arlington	**1997-2003**
Assistant Professor, University of Texas at Arlington	**1993-1997**
Research Fellow, University of Michigan	**1989-1992**
Research Associate, Indiana University	**1988-1989**

Publications – closely related to proposed project

1. The ATLAS Experiment at the CERN Large Hadron Collider, The ATLAS Collaboration, G. Aad et al., JINST 3 (2008) S08003.
2. The ATLAS Simulation Infrastructure, The ATLAS Collaboration, G. Aad et al., Eur. Phys. J. C (2010) 70: 823–874.
3. Contributions to CHEP15 (eight papers on Computing in HEP): http://indico.cern.ch/event/304944/session/10/contribution/100/author/2.
4. SUSY1
5. SUSY2

Synergistic Activities

a) **Leadership in Physics at the New Frontier**: leading a large group of researchers and students at UTA in the cutting edge research projects in the ATLAS experiment at the Large Hadron Collider at CERN, Geneva, Switzerland, since 1995. Many masters and Ph.D. students and postdocs in Physics supervised.

b) **Big Data Innovation**: led the development of a new paradigm in computing over the past decade: the PanDA software, which provides physicists automatic access to hundreds of supercomputing centers internationally. Thousands of physicists analyze data and publish results in multiple High Energy Physics (HEP) experiments using PanDA. Supervised/co-supervised many masters and Ph.D. theses in Computer Science on PanDA.

c) **New Discoveries**: played key roles in many aspects of the HEP experiments that discovered two fundamental particles in physics over the past two decades: the top quark at the Tevatron, and the Higgs boson at the LHC.

d) **New Physics searches**: early proponent of the search for the supersymmetric partner of the top quark in both the D0 and the ATLAS experiments at the LHC. Supervised multiple Ph.D. students who completed theses in D0 and ATLAS on this topic.

e) **Supercomputing technology**: founding director of the SouthWest Tier 2 supercomputing center, located at UTA and Oklahoma University. Funded by multiple grants from National Science Foundation, and the Department of Energy.

Collaborators

The D0 collaboration (see http://www-d0.fnal.gov/~madaras/authorlist.html)
The ATLAS collaboration (see http://graybook.cern.ch/programmes/experiments/lhc/ATLAS.html)

Graduate and Postdoctoral Advisors

Prof. Mildred Widgoff (Brown University), Prof. Andrej Zieminski (Indiana University), Prof. Homer Neal (University of Michigan).

Graduate Student Advisees

Yan Song (IBM), Barry Spurlock (UTA), Rishiraj Pravahan (AT&T), Smita Darmora (UTA), Jared Little (UTA), Ted Eltzroth (unknown), Nevzat Guler (unknown), Richard Kaiser (NRC), Yu Xia (unknown).

Postdoctoral Associates

Elizabeth Gallas (Oxford), Jia Li (deceased), Mark Sosebee (UTA), Armen Vartapetian (UTA), Nurcan Ozturk (UTA), Paul Nilsson (BNL), Alden Stradling (UTA), Giulio Usai (UTA), David Cote (Ciena).

Haleh Hadavand

Education and Training

Undergraduate: University of Maryland College Park **College Park, MD**
Sep 1995 - Jun 1999
Degree: BS in Physics, June 1999.

Graduate: University of California San Diego **La Jolla, CA**
Aug 1999 - Sept 2005
Degree: Ph.D. in High Energy Physics Dissertation: "The Measurement of CP Asymmetries in the Three-body Charmless B_d Meson Decay to $K^0_S K^0_S K^0_S$ at BABAR "
Thesis adviser: David MacFarlane.

Research and Professional Experience

Assistant Professor **University of Texas Arlington**
Nov 2014 - Present

Research Faculty **University of Texas Arlington**
July 2012 - Oct 2014

Postdoctoral Fellow **Southern Methodist University**
Sept 2005-July 2012

Graduate Research Assistant **UCSD on BABAR experiment**
Jun 1999 - Sept 2005

Relevant Publications

[1] The ATLAS Collaboration, "Search for charged Higgs bosons decaying via $H^{\pm} \to \tau^{\pm}\nu$ in fully hadronic final states using pp collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector", JHEP03 (2015) 088.

[2] The ATLAS Collaboration, "A Search for Charged Higgs Bosons in the τ +jets Final State with pp Collision Data Recorded at $\sqrt{s} = 8$ TeV with the ATLAS Experiment", ATLAS-CONF-2013-090 (2013).

[3] The ATLAS Collaboration, "Search for extra dimensions using diphoton events in 7 TeV proton-proton collisions with the ATLAS detector", Phys. Lett. B **710**, 538-556 (2012).

[4] The ATLAS Collaboration, "A Search for High Mass Diphoton Resonances in the Context of the Randall-Sundrum Model in $\sqrt{s} = 7$ TeV pp Collisions", ATLAS-CONF-2011-044 (2011).

[5] The ATLAS Collaboration, "Search for Diphoton Events with Large Missing Transverse Energy in 7 TeV Proton-Proton Collisions with the ATLAS Detector", Phys. Rev. Lett. **106**, 121803 (2011).

[6] Ilchenko, Y., Cuenca-Almenar, C. , Corso-Radu, A., Hadavand, H. Kolos, S, Slagle, K., Taffard, A.,"Data Quality Monitoring Display for ATLAS experiment", J. Phys. Conf. Ser. **219**, 022035 (2010).

[7] H. Hadavand [ATLAS Collaboration], "Commissioning of the ATLAS offline software with cosmic rays", J. Phys. Conf. Ser. **119**, 032021 (2008).

[8] S. Kolos, A. Corso-Radu, H. Hadavand, M. Hauschild, R. Kehoe, "A software framework for Data Quality Monitoring in ATLAS", J. Phys. Conf. Ser. **119**, 022033 (2008).

[9] B. Aubert *et al.* [BABAR Collaboration], "Branching Fraction and CP Asymmetries in $B^0 \to K^0_S K^0_S K^0_S$", Phys. Rev. Lett. **95**, 011801 (2005).

[10] B. Aubert *et al.* [BABAR Collaboration], “Measurement of the B^+/B^0production ratio from the $\Upsilon(4S)$meson using $B^+\to J/\psi \mathrm{K}^+$ and $B^0\to J/\psi K^0_S$decays”, Phys. Rev. D **69**, 071101 (2004). “New Physics results from the BABAR Collaboration”, July 2005.

Synergistic Activities

Invited Talks

[11] Lake Louise Winter Institute, Lake Louise, Alberta, Canada, “Beyond-the-Standard Model Higgs and Invisible Higgs Decays Using the ATLAS Experiment”, February 2014.

[12] Photon 2011 Conference at Spa, Belgium, “New Physics Searches with Photons at the ATLAS and CMS Experiments”, May 2011.

[13] Beyond Standard Model Physics Conference, Boston, MA., “Beyond the Standard Model Photon Physics at the ATLAS and CMS Experiments at the Large Hadron Collider”, June 2009.

Leadership Experience

- Charged Higgs convenor on the ATLAS experiment.
- Co-editor of paper and conference note on extra dimension diphotons resonances [3, 4].

Collaborators and Co-editors

Maria Pilar Casado, Universitat Autònoma de Barcelona, Arnaud Ferrari, Uppsala University, Thomas Junk, Fermilab, Anna Kopf, Freiburg University, Allison McCarn, Univerisity of Michigan, Henrik Ohman, Uppsala University, Michael Pitt, Weizmann Institute of Science, John Parsons, Columbia University, Nikolaos Rompotis, University of Wisconsin, Jana Schaarschmidt, Weizmann Institute of Science, Stephen Sekula, Southern Methodist University, Camila Rangel Smith, Uppsala University, Michelle Stancari, Fermilab.

Graduate and Postdoctoral Advisors and Advisees

Rozmin Daya-Ishmukhametova, University of Massachusetts - Amherst, Yuriy Ilchenko, UT Austin, Renat Ishmukhametov, Ohio State University,Bob Kehoe, Southern Methodist University, Ryszard Stroynowski, Southern Methodist University.

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EDUCATION AND TRAINING

- **Research Associate**, Fermi National Accelerator Laboratory, **1996-1998**
- **Research Fellow**, University of Rochester, **1993-1996**
- **Ph.D.**, Physics, State University of New York, Stony Brook, **1993**
- **M.S.**, Physics,State University of New York, Stony Brook, **1992**
- **M.A.**, Physics, Korea University, Seoul, South Korea, **1985**
- **D.S.**, Physics, Korea University, Seoul, South Korea, **1983**

RESEARCH AND PROFESSIONAL EXPERIENCE

- **Professor**, University of Texas at Arlington, **2012–present**
- **Associate Professor**, University of Texas at Arlington, **2006–2012**
- **Assistant Professor**, University of Texas at Arlington, **2001–2006**
- **Associate Scientist**, Fermi National Accelerator Laboratory, **1998-2001**

SELECTED PUBLICATIONS

1. ATLAS Collaboration, Measurement of exclusive $\gamma\gamma \to W^+W^-$ Production and search for exclusive Higgs boson production in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector, Phys. Rev. **D 94**, 032011 (2016)
2. ATLAS Collaboration, Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at s=7 and 8 TeV in the ATLAS experiment, arXiv:1507.04548 [hep-ex]
3. Georges Aad et al., ATLAS Collaboration, Study of (W/Z)H production and Higgs boson couplings using HWW decays with the ATLAS detector, JHEP 1508 (2015) 137.
4. Keisuke Fujii et al., Linear Collider Physics Panel, Physics Case for the International Linear Collider, arXiv:1506.05992 [hep-ex].
5. CMS and ATLAS Collaborations, Combined Measurement of the Higgs Boson Mass in pp Collisions at s=7 and 8 TeV with the ATLAS and CMS Experiments, Phys.Rev.Lett. 114 (2015) 191803.
6. Georges Aad et al., ATLAS Collaboration, Search for a Charged Higgs Boson Produced in the Vector-Boson Fusion Mode with Decay HWZ using pp Collisions at s=8TeV with the ATLAS Experiment, Phys.Rev.Lett. 114 (2015) 23, 231801.
7. C. Adams et al., LBNE Collaboration, The Long-Baseline Neutrino Experiment: Exploring Fundamental Symmetries of the Universe, arXiv:1307.7335 (2014)
8. H. Frisch, C. Hast, E. Ramberg, M. Artuso, A. Seiden, M. Wetstein, M.C. Sanchez & J. Fast, et al, Compendium of Instrumentation Frontier Whitepapers on Technologies for Snowmass 2013
9. Georges Aad et al., ATLAS Collaboration, Search for dark matter in events with heavy quarks and missing transberse momentum in pp collisions at s =7 TeV with the ATLAS detector arXiv:1410.4031 (2014)
10. Georges Aad et al., ATLAS Collaboration, Search for neutral Higgs boson of the minimal supersymmetric standard model in pp collisions at s =8 TeV with the ATLAS detector JHEP 1411 (2014) 056

SYNERGISTIC ACTIVITIES

1. **Aug. 2016 present:** Executive Board member, WA105 experiment at CERN
2. **Nov. 2015 present:** Institutional Board member, ICARUS experiment at CERN/Fermilab
3. **Sept. 2015 present:** DUNE Beyond the Standard Model physics group co-convener
4. **Mar. 2015 present:** Institutional Board representative, Deep Underground Neutrino Experiment at Fermilab
5. **Aug. 2013 Jan. 2015:** LBNE R&D Coordinating committee co-convener

COLLABORATORS:ATLAS, CALICE, SiD, LBNE, LArIAT and ORKA Collaborations

GRADUATE AND POSTDOCTORAL ADVISORS

- **Dr. Robert Bernstein**, Fermilab, PostDoctoral Advisor:**1996–1998**
- **Prof. Frederick Lobkowitz (deceased)**, Univ. of Rochester, PostDoctoral Advisor:**1993–1996**
- **Prof. Robert L. McCarthy**, SUNY Stony Brook, Thesis Advisor:**1988–1993**

POSTDOCTORAL ADVISEES

1. **Dr. Animesh Chatterjee**, Postdoctoral Fellow, University of Texas at Arlington, **2014-present.**
2. **Dr. Justin Griffiths**, Postdoctoral Fellow, University of Texas at Arlington, **2012-present.**
3. **Dr. Seongtae Park**, Senior Postdoctoral Fellow, University of Texas at Arlington, **2010-2014**
4. **Dr. Hyunwoo Kim**, Postdoctoral Fellow, University of Texas at Arlington, **2004-2007, currently an associate scientist at Fermilab**
5. **Mr. Sudhamshi Reddy**, Software Engineer, University of Texas at Arlington, **2007-2009, currently on UTA Computer Science and Engineering Ph.D. candidate**

GRADUATE STUDENT ADVISEES

1. **Garrett Brown**, Ph.D., Univ. of Texas at Arlington, **2016 - present**
2. **Last Feremenga**, Ph.D., Univ. of Texas at Arlington, **expected to graduate in 2016**
3. **Heeyeun Kim**, Ph.D., Univ. of Texas at Arlington, **2015 - Researcher at Harvard Medical School**
4. **Dr. Jacob Smith**, Ph.D., Univ. of Texas at Arlington, **2013–PostDoc at U. of Maryland**
5. **Dr. Hyeonjin Kim**, Ph.D., Univ. of Texas at Arlington, **2010–PostDoc at U. of Stockholm, Sweden**
6. **Dr. Venkatesh Kaushik**, Ph.D., Univ. of Texas at Arlington, **2007–** EMC^2
7. **Jacob Smith**, M.S., Univ. of Texas at Arlington, **2010–Continued into the Ph.D. program at UTA**

Biographical Sketch
Jonathan Asaadi

Education and Training

Institution	**Location**	**Major**	**Degree & Year**
Undergraduate Institution	University of Iowa	Physics	B.S. 2004
Graduate Institution	Texas A&M University	Physics	M.S. 2007
Graduate Institution	Texas A&M University	Physics	PhD. 2012
Postdoctoral Institution	Syracuse University	Neutrinos	2012-2015

Research and Professional Experience

Assistant Professor	University of Texas Arlington	2015 – Present
Postdoctoral Researcher	Syracuse University	2012 – 2015

Publications

- *"Measurement of ν_μ and $\bar{\nu}_\mu$ Neutral Current $\pi^0 \rightarrow \gamma\gamma$ Production in the ArgoNeuT Detector"*,
Submitted to PRD (2014), arXiv:1511.00941 (Primary author and primary analyzer)

- *"Testing of High Voltage Surge Protection Devices for Use in Liquid Argon TPC Detectors"*,
JINST 9 P09002 (2014), arXiv:1406.5216 (Primary author and primary analyzer)

- *"The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT detector in the NuMI low energy beam"*
Phys. Rev. D 90, 012008 (2014), arXiv:1405.4261 (Reviewer and collaborator)

- *"Measurements of Inclusive Muon Neutrino and Antineutrino Charged Current Differential Cross Sections on Argon in the NuMI Antineutrino Beam"*
Phys. Rev. D 89, 112003 (2014), arXiv:1404.3698 (Collaborator)

- *"A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam"*
arXiv:1503.01520 (Collaborator)

- "*ArgonCube: a no*vel, fully-modular approach for the realization of large-mass liquid argon TPC neutrino detectors"
CERN-SPSC-2015-009 ; SPSC-I-243 (Contributing author and analyzer)

- *"LAr1-ND: Testing Neutrino Anomalies with Multiple LArTPC Detectors at Fermilab"*
Snowmass White Paper SNOW13-00176, arXiv:1309.7987 (Collaborator)

- *"Signature-based search for delayed photons in the exclusive photon plus missing transverse energy events from proton anti-proton collisions with center of mass energy = 1.96 TeV"*
Phys. Rev. D 88, 031103 (2013), arXiv:1307.0474 (Primary author and primary analyzer)

- "*LArIAT: Liquid Argon In A Testbeam"*
arXiv:1406.5560 (Collaborator)

Synergistic Activities

- Neutrino Detector R&D Facilities Workshop
Organizing Committee Member, January 2016

- **The Liquid Argon TPC Reconstruction Assessment and Requirement Workshop**
Organizing Committee Member, November 2015

- Albert Einstein Center Visiting Fellow 2014, Laboratory for High Energy Physics (LHEP), University of Bern Switzerland

- **Coordinating Panel for Advanced Detectors (CPAD) Instrumentation Frontier Meeting**
Invited Talk “New Technologies for Neutrino Oscillations”, October 2015

- 25th Workshop on Weak Interactions and Neutrinos (WIN2015)
Invited Talk “The Fermilab Short-Baseline Neutrino Program”

Collaborators

Collaborators and Co-Editors:

Adam Aurisano	University of Cincinnati	Collaborator
Bruce Baller	Fermilab	Collaborator
Tim Bolton	Kansas State University	Collaborator
Carl Bromberg	Michigan State University	Collaborator
Flavio Cavanna	Fermilab	Collaborator
Eric Church	Pacific Northwest National Laboratory	Collaborator
Janet Conrad	Massachusetts Institute of Technology	Collaborator
Bhaskar Dutta	Texas A&M	Graduate Advisor
Antonio Ereditato	Bern University	Collaborator
Bonnie Fleming	Yale University	Collaborator
Teruki Kamon	Texas A&M University	Graduate Advisor
Igro Kreslo	Bern University	Collaborator
Ornella Palamara	Fermilab	Collaborator
Jennifer Raaf	Fermilab	Collaborator
Brian Rebel	Fermilab	Collaborator
Mitch Soderberg	Syracuse University	Post-doctoral Advisor
Josh Spitz	University of Michigan	Collaborator
Andrzej Szlec	Manchester University	Collaborator
David Toback	Texas A&M University	Graduate Advisor (Chair)
Michele Weber	Bern University	Collaborator
Tingjun Yang	Fermilab	Collaborator
Geralyn Zeller	Fermilab	Collaborator

Graduate Advisors and Postdoctoral Sponsors
Prof. David Toback (Texas A&M)
Prof. Mitch Soderberg (Syracuse University)

Current and Pending Support: Andrew Brandt

Support: ☒ Awarded ☐ Pending	
Sponsor: DOE	**Award/Identifying Number:** 209151
Proposal Title: Research in Experimental Elementary Particle Physics (co-PI)	
Total Award Amount for the Entire Award Period (including indirect costs): $2,520,000	
Award Period: 5/01/2014- 3/31/2017	
Number of Person-months per year to be devoted to the project: 1.0	
Abstract: Base funding for the UTA HEP group to support their summer salaries, post-docs, students, and travel. This umbrella proposal encompasses various activities in the energy frontier primarily for ATLAS: data analysis in Higgs and SUSY, trigger development, major leadership roles in computing, etc., with a modest effort in ILC development and leadership; and the intensity frontier ranging from Lariat to Dune.	

Support: ☒ Awarded ☐ Pending	
Sponsor: DOE	**Award/Identifying Number:** 215078
Proposal Title: Development of a Long Life Photomultiplier Tube for High Flux Applications (PI)	
Total Award Amount for the Entire Award Period (including indirect costs): $125,000	
Award Period: 6/01/2015- 3/31/2017	
Number of Person-months per year to be devoted to the project: 1.0	
Abstract: This project seeks is concerned with the development of long-life microchannel plate (MCP) photomultiplier tubes (PMTs), capable of high rate operation. Its goals are the optimization of lifetime testing methods including the efficacy of multiple lifetime measurements per device, expedited lifetime measurements, and after-pulsing studies that seek to correlate lifetime with the amount of specific heavy ions.	

Support: ☒ Awarded ☐ Pending	
Sponsor: Department of Education	**Award/Identifying Number:**
Proposal Title: Reaching Goals in Physics with GAANN Fellowships (Co-Pi)	
Total Award Amount for the Entire Award Period (including indirect costs): $536,688	
Award Period: 9/01/2016- 8/31/2019	
Number of Person-months per year to be devoted to the project: 0.5	
Abstract: This proposal provides funding for physics graduate students with demonstrated need for financial aid, and includes a supervised teaching requirement.	

Support: ☐ Awarded ☒ Pending	
Sponsor: DOE	**Award/Identifying Number:**
Proposal Title: Research in Experimental Elementary Particle Physics (co-PI)	
Total Award Amount for the Entire Award Period (including indirect costs): $	
Award Period: 4/01/2017- 3/31/2020	
Number of Person-months per year to be devoted to the project: 2.0	
Abstract: Renewal of base funding for the UTA HEP group to support their summer salaries, post-docs, students, and travel. This umbrella proposal encompasses various activities in the energy frontier primarily for ATLAS: data analysis in Higgs and SUSY, trigger development, major leadership roles in computing, and TileCAl, with a modest effort in ILC development and leadership; and the intensity frontier ranging from Lariat to Dune.	

Current and Pending Support: Kaushik De

Support: ☒ Awarded ☐ Pending	
Sponsor: NSF	**Award Number**: NSF PHY-1119200
Title of the Funded Research Project: The U.S. ATLAS Research Program: Empowering U.S. Universities for Discoveries at the Energy Frontier	
Total Award Amount for the Entire Award Period (including indirect costs): $1,611,368	
Award Period: 10/01/15 - 9/30/16	
Number of Person-months per year to be devoted to the project by the PI: 2.0	
Abstract: UTA is a sub-contractor of the NSF US ATLAS Operations program cooperative agreement managed by Columbia University. This cooperative agreement supports M&O, S&C and R&D activities on the ATLAS experiment at the LHC. Activities at UTA include the operation of the SouthWest Tier 2, PanDA software development, US Computing Operations, Analysis support and documentation, and TileCal detector operation and upgrade R&D. These support activities are critical to the success of the ATLAS physics program.	

Support: ☒ Awarded ☐ Pending	
Sponsor:	**Award Number**: BNL Contract #229206
Title of the Funded Research Project: The U.S. ATLAS Research Program	
Total Award Amount for the Entire Award Period (including indirect costs): $282,000	
Award Period: 10/01/14 - 9/30/16 (NCE)	
Number of Person-months per year to be devoted to the project by the PI: 0	
Abstract: UTA receives DOE funding for M&O and S&C activities in support of the US ATLAS Research Program through Brookhaven National Laboratory. Supported activities at UTA include the operation of the SouthWest Tier 2, and TileCal detector operation and upgrade R&D. These support activities are critical to the success of the ATLAS physics program.	

Support: ☒ Awarded ☐ Pending	
Sponsor: DOE	**Award Number**: DOE DE-SC0011686
Title of the Funded Research Project: High Energy Physics Base Funding	
Total Award Amount for the Entire Award Period (including indirect costs): $890,000	
Award Period: 05/01/16 - 04/31/17	
Number of Person-months per year to be devoted to the project by the PI: 2.0	
Abstract: This proposal requests support for a program of research in elementary particle physics at The University of Texas at Arlington. We propose studies of the recently discovered Higgs boson, and searches for new particles in nature which may be responsible for dark matter, at the ATLAS Experiment at the European Center for Nuclear Research (CERN) in Geneva, Switzerland, and the Silicon Detector (SiD) at the proposed International Linear Collider. The SiD is a novel concept for a future experiment in particle physics. Our program of work involves detector research and development, and distributed computing innovations. Together, the ATLAS Experiment and SiD can provide a deep understanding of two fundamental forces of nature: electromagnetism and the weak nuclear force, in addition to allowing for the discovery of associated new particles suggested by theory. In a new direction for the group, support is also requested for participation in the future Long Baseline Neutrino Experiment (LBNE), which will explore the masses of the neutrinos that are involved in the weak nuclear interactions and search for low-mass dark matter in the beam, and the ORKA Experiment, that will search for signs of new physics in the rare decays of the K-meson, a particle only produced in high energy collisions. Finally, we propose to carry out theoretical studies of the dark matter that exists in large quantities around and between galaxies, in terms of its interactions with astrophysical objects, and its possible creation in low-energy, high beam intensity experiments.	

Support: ☒ Awarded ☐ Pending	
Sponsor: DOE	**Award Number**: DOE DE-SC008635
Title of the Funded Research Project: Next Generation Workload Management and Analysis System for Big Data	
Award Period: 9/01/12 - 08/31/16 (NCE)	
Total Award Amount for the Entire Award Period (including indirect costs): $746,908	
Number of Person-months per year to be devoted to the project by the PI: 1.0	
Abstract: One of the largest scientific collaborations ever assembled, the ATLAS experiment at the Large Hadron Collider (LHC), is designed to explore the fundamental properties of matter for the next decade. An important foundation underlying the impressive success of ATLAS data processing and analysis is the Production and Distributed Analysis (PanDA) workload management system. We propose here a program to develop a generic version of PanDA which can be easily used by many data intensive sciences. With a modest investment of effort, we can enable easy adoption of PanDA by others. We propose generalizing PanDA as a meta-application, providing location transparency of processing and data access, for High Energy Physics, other data-intensive sciences, and a wider exascale community.	

Support: ☒ Awarded ☐ Pending	
Sponsor: DOE	**Award Number**: DOE DE-SC0016280
Title of the Funded Research Project: Big PanDA Workflow Management on Titan for High Energy and Nuclear Physics and for Future Extreme Scale Scientific Applications	
Award Period: 7/01/16 - 06/30/18	
Total Award Amount for the Entire Award Period (including indirect costs): $1.063,000	
Number of Person-months per year to be devoted to the project by the PI: 1.0	
Abstract: Scientific priorities in High Energy and Nuclear Physics continue to serve as drivers of integrated computer and data infrastructure. The lack of scalable and extensible workload management capabilities across heterogeneous computing infrastructure, however presents a barrier to the scientific progress. BigPanDA represents important conceptual advances and novel capabilities to workload management. We propose to deploy and bring into production BigPanDA workflow management techniques on the Oak Ridge Leadership Computing Facility (OLCF) Titan supercomputer. This will significantly and positively impact scientific communities in High Energy and Nuclear Physics, and beyond, for current and future leadership computing facilities.	

Current and Pending Support: Andrew P. White

Support: ☒ Awarded ☐ Pending	
Sponsor: DOE	**Award Number**: DOE DE-SC0011686
Title of the Funded Research Project: Research in Elementary Particle Physics	
Total Award Amount for the Entire Award Period (including indirect costs): $890,000	
Award Period: 04/01/16 - 03/31/17	
Number of Person-months per year to be devoted to the project by the PI: 2.0	
Abstract: This project supports the work of the UTA HEP group for the Energy and Intensity Frontiers. For the Energy Frontier, activities for the ATLAS experiment include leadership in computing and software, support for the operation and calibration of the Tile Calorimeter, physics studies in the SUSY and Higgs sectors, and upgrade work on TDAQi and low voltage power supplies. Also for the Energy Frontier, we have a Spokesperson role in the SiD Consortium for the International Linear Collider. Activities for SiD include the development of the design of the SiD Detector, establishing the SiD Consortium as a precursor to a full detector collaboration, promotion and coordination all aspects of detector R\&D and physics and performance studies, and representation of SiD within the HEP community nationally and internationally. For the Intensity Frontier efforts include optimization of LBNF beam line for DUNE, Design and construction of proton beam alignment monitor (PBAM) for DUNE, aka hadron monitor, optimization of Optical Coupling for DUNE photo detectors, DUNE 35t Data Analysis and Operations, studies for subGeV Dark Matter, Phase I LArIAT experiment data analyses, MiniBooNE beam dump data analysis, and contributions to Fermilab onsite long baseline experiments.	

Support: ☐ Awarded ☒ Pending	
Sponsor: DOE	**Award Number**:
Title of the Funded Research Project: Research in Elementary Particle Phyiscs	
Total Award Amount for the Entire Award Period (including indirect costs): $?????	
Award Period: **04**/01/17 - 03/31/20	
Number of Person-months per year to be devoted to the project by the PI: 2.0	
Abstract:	

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Current and Pending Support: Haleh Hadavand

Current and Pending Support
Support: ☒ Awarded ☐ Pending
Sponsor: ATLAS Project Funds Award/Identifying Number:
Title of the Proposal: Request Beyond Target for Tile Low Voltage Power Supplies
Total Award Amount for the Entire Award Period (including indirect costs): $58,000
Award Period: **1/30/16-9/30/16**
Number of Person-months per year to be devoted to the project: 0.0
Abstract:

Current and Pending Support
Support: ☐ Awarded ☒ Pending
Sponsor: NSF **Award/Identifying Number:** 1654772
Title of the Proposal: Search for Beyond Standard Model Phenomena with Tau Leptons and Higgs
Total Award Amount for the Entire Award Period (including indirect costs): $810,011
Award Period: **2017 – 2022**
Number of Person-months per year to be devoted to the project: 2 months/year

Current and Pending Support: Jaehoon Yu

Support: ☒ Awarded ☐ Pending	
Sponsor: DOE	**Award Number**: DOE DE-SC0011686
Title of the Funded Research Project: Research on Elementary Particle Physics	
Total Award Amount for the Entire Award Period (including indirect costs): $890,000	
Award Period: 04/01/16 - 03/31/17	
Number of Person-months per year to be devoted to the project by the PI: 2.0	
Abstract: This proposal requests support for a program of research in elementary particle physics at The University of Texas at Arlington. We propose studies of the recently discovered Higgs boson, and searches for new particles in nature which may be responsible for dark matter, at the ATLAS Experiment at the European Center for Nuclear Research (CERN) in Geneva, Switzerland, and the Silicon Detector (SiD) at the proposed International Linear Collider. The SiD is a novel concept for a future experiment in particle physics. Our program of work involves detector research and development, and distributed computing innovations. Together, the ATLAS Experiment and SiD can provide a deep understanding of two fundamental forces of nature: electromagnetism and the weak nuclear force, in addition to allowing for the discovery of associated new particles suggested by theory. In a new direction for the group, support is also requested for participation in the future Long Baseline Neutrino Experiment (LBNE), which will explore the masses of the neutrinos that are involved in the weak nuclear interactions and search for low-mass dark matter in the beam, and the ORKA Experiment, that will search for signs of new physics in the rare decays of the K-meson, a particle only produced in high energy collisions. Finally, we propose to carry out theoretical studies of the dark matter that exists in large quantities around and between galaxies, in terms of its interactions with astrophysical objects, and its possible creation in low-energy, high beam intensity experiments.	

Support: ☒ Awarded ☐ Pending	
Sponsor: National Cancer Institute, National Health Institute	**Award Number**: 1R15CA199020-01A1
Title of the Funded Research Project: Boosting photo-induced cancer therapies through real-time image guidance	
Total Award Amount for the Entire Award Period (including indirect costs): $415,336	
Award Period: 04/01/16 - 03/31/19	
Number of Person-months per year to be devoted to the project by the PI: 0.2	
Abstract: We propose to use the position-sensitive gas electron multiplier (GEM) detector and advanced spatiotemporal image processing to enable real-time image guided PITs. The GEM technology is a recent advance of the revolutionary digital imaging of gas detectors using multiwire proportional chambers (MWPC), which won Georges Charpak a Nobel Prize for Physics in 1992. The advantages of GEM-based devices include: intrinsic spatial resolution of 50 µM or better; rate capability lager than 1MHz/mm^2; easy achievable gains above $10^{5;}$ allowing detection of single electrons; efficiency for minimum ionizing particles close to 100%. In additional to its excellent detection performance, the flexibility of GEM can be used for a miniature device with the easy integration of an NIR fiber for therapeutic purpose. In this project, for the first time, we propose to develop a multifunctional device using GEM technology for PITs, called Ò{\bf Beta Image Guided Light-Induced Therapeutic device (BIGLITE)}, which can achieve simultaneous imaging and photo-induced therapy.	

Support: ☒ Awarded ☐ Pending	
Sponsor: NSF	**Award Number**: 1639157
Title of the Funded Research Project: Support for Biennial African School of Fundamental Physics 2016	
Total Award Amount for the Entire Award Period (including indirect costs): $28,215	
Award Period: 07/01/16 - 06/30/17	
Number of Person-months per year to be devoted to the project by the PI: 0.01	
Abstract: This proposal is in support of the forth school in the biennial series. The aim of the school is to build the capacity to harvest, interpret, and exploit the results of current and future physics experiments with particle accelerators, and to increase proficiency in related applications such as medicine, and technologies, such as grid computing. The schools are based on a close interplay between theoretical, experimental and applied physics. The organizing committee consists of a number of people key in the above areas, from both inside and outside Africa. Sub-Saharan Africa is under-represented in sub-atomic physics and this school will serve to provide more opportunities for students to become aware of and to participate in this field.	

Support: ☒ Awarded ☐ Pending	
Sponsor: Fermi National Accelerator Laboratory	**Award Number**: N/A
Title of the Funded Research Project: Application for Neutrino Physics Center Fellowship	
Award Period: 07/01/16 - 06/30/17	
Total Award Amount for the Entire Award Period (including indirect costs): $10,000	
Number of Person-months per year to be devoted to the project by the PI: 1.5	
Abstract: The major goals of this project are to understand the behavior of the membrane cryostat, develop and design the beam hadron monitor and optimize the beam line components for DUNE experiment. These funds enable the PI to contribute directly to DUNE experiment through an extended stay at FNAL.	

Support: ☒ Awarded ☐ Pending	
Sponsor: CNRS, France	**Award Number**: 1263101510
Title of the Funded Research Project: MOU for Research on WA105 Dual Phase Detector and DUNE	
Award Period: 10/01/15 - 12/31/17	
Total Award Amount for the Entire Award Period (including indirect costs): $36,728	
Number of Person-months per year to be devoted to the project by the PI: 1.0	
Abstract: The major goal of this project is to contribute to the setup of WA105 and understanding DUNE cryostats.	

Support: ☒ Awarded ☐ Pending

Sponsor: Brookhaven National Lab (DOE) **Award Number**:

Title of the Funded Research Project: Development of SiPM Coupling with Scintillation Counters for Range Stack Detector

Award Period: 10/01/13 - 09/30/16

Total Award Amount for the Entire Award Period (including indirect costs): $46,000

Number of Person-months per year to be devoted to the project by the PI: 0.1

Abstract: The Range Stack (RS) in ORKA detector plays an essential role in particle identification, especially the pions from Kaon decays from muons. It must be able to measure the energy, range and decay sequence of charged particles emerging from the target with a good position resolution. In addition, it must able to assist photon veto (PV) detector by identifying them with good efficiency for the photons converting before getting into the PV system. These funds have been repurposed to support LBNE/DUNE photo detector R&D of the same topic.

Current and Pending Support: Jonathan Asaadi

Current and Pending Support
Support: ☐ Awarded ☒ Pending
Sponsor: NSF **Award/Identifying Number: 1654507**
Title of the Proposal: CAREER: A novel fully modular liquid argon neutrino detector for the Deep Underground Neutrino Experiment
Total Award Amount for the Entire Award Period (including indirect costs): $1,114,875
Award Period: **2017 - 2021**
Number of Person-months per year to be devoted to the project: 2 months/year
Abstract: This proposal puts forward the development of a new modular liquid argon time projection chamber (LArTPC) neutrino detector to be used as a near detector for the Deep Underground Neutrino Experiment (DUNE). The ultimate goal of this project is to demonstrate the feasibility of constructing and operating identical but separate LArTPC modules in a common bath of liquid argon. Each module features a relatively short drift length and at a fully independent TPC with its own readout, light detection system, cryogenics, and services.

FACILITIES AND OTHER RESOURCES

The University of Texas (UTA) is the second largest university in the UT system with around 35,000 students. It is a comprehensive doctoral university located in the Dallas-Ft. Worth metroplex. HEP was selected as one of the first ”Organized Research Center of Excellence” at UTA in 2011. PI De is the Director of the ORCE:HEP Center, which also includes faculty from commology, astrophysics, space sciences, and computtational sciences. The combined synergy of these activities, along with substantial commitment of university resources, provides strong support to the core DoE HEP mission at UTA. Overall, the university has invested over two million dollars to support HEP research activities.

A prime example of UTA's investment in science was the provision of the 120,000 sq.ft. Physics and Chemistry Research Building in 2006. This building houses a high bay area for HEP, our ATLAS Tier 2 center, three detector development laboratories, an HEP conference room, faculty offices, and postdoc and graduate student offices. The building houses an excellent Physics mechanical workshop with the capabilities to manage large scale detector construction..

One finished lab space at UT Arlington's Physics and Chemistry Research Builiding is a 700 sq. feet lab space with the necessary ventilation for cryogenic experiments to take place. This lab space has recently been completed with a purification and pressure based gas recirculation system for liquid argon detector R&D.

The finished lab space also houses desk space, computers, soldering stations, and work space for the undergraduate detector sensor lab as well as a intensity frontier remote operations center. This remote operation center has already been used to take shifts on the LArIAT experiment and is being expanded for remote shift taking on MicroBooNE, SBND, and ICARUS.

A 700 sq feet unfinished lab space adjacent to the purified liquid argon lab and located off the high-bay area has a 3 ton crane for detector construction and assembly. This lab space is located directly adjacent to the UTA physics department machine shop which can be used during detector testing and construction.

In addition to this lab space, the UTA HEP group have retained our previous office suite in Science Hall, and this area has been rennovated as the ATLAS Tier 2 operations and visitors area. The lab space in the basement of Science Hall now houses the purified gaseous xenon system as well as (need words from David and Ben)

UTA hosts the SouthWest Tier 2 center (SWT2) for ATLAS, which is one of the largest computing centers for ATLAS, providing over 3000 cores and 3 petabytes of storage. The UTA HEP Tier 3 center is co-located with the Tier 2, providing easy access to ATLAS data.