## Abstract

# Cover Page Supplement

Part I
# UTA Group Introduction

## UTA Group Introduction

# Part II
# Research at the Energy Frontier

## PI Summary: Andrew White

## PI Summary: Kaushik De

## PI Summary: Andrew Brandt

## PI Summary: Amir Farbin

Motivation ———- * Naturalness/Dark Matter/Unification =¿ Razor/Jigsaw (ICHEP2016) =¿ Jigsaw+DNN =¿ Compressed spectra =¿ bbll+MET topological searches =¿ General Searches @ end of Run 2 =¿ Run 3 =¿ HL-LHC Physics =¿ DM searches in Neutrino Beams =¿ mini-BooNE/DUNE (Sepideh) =¿ Advanced techniques: MEMs, DNNs (overlap with computing)

* Computing Problems =¿ LArTPC Reco =¿ LArIAT DNN Classification and Energy Regression. =¿ HL-LHC Computing- Need order magnitude cost saving. =¿ Moore's Law and Parallelism =¿ New Frameworks + New processors + DNNs =¿ Better, Faster, Easier/Cheaper =¿ DNNs =¿ TrackingML Dataset =¿ Computationally Extending Physics Reach =¿ DNNs encapsulation of MEM (Tancredi Carli + Hussien) =¿ Generative DNN replacing Simulation/Geant4 =¿ DNN-based Calorimetry: better classification and energy resolution. =¿ LCD Calorimeter (J.R. Vlimant Maria Spiropulu's and Maurizio Pierini from CERN) =¿ ATLAS Calorimeter (Taylor Childers ? )

Uniqueness ———-

* Connected to computing at 2 frontiers, (experience: ATLAS PAT + DUNE Management) =¿ Working relationships with key core-framework developers (art, cmssw, athena) and others (gaudi, Geant V). =¿ + Community Whitepaper =¿ Frameworks workshop =¿ LHC/DUNE expertise exchange (somewhat on hold =¿ Art Framework mini-workshop =¿ WMS/DDM mini-workshop : First time FIFE/CMS/PANDA together? =¿ Requirements

* Leader in Deep Learning in HEP (lots of big talks + workshop organizer) =¿ Working relationships/collaboration with full DNN in HEP community. =¿ Initiating many and facilitating other projects. =¿ Many collaborative papers in the works (see below). =¿ DNN Services: More than an dozen HEP DNN users of my machine from 6 experiments. =¿ provide full list? =¿ Datasets: LArTPC, Calorimetry, Tracking =¿ Significant number of interesting results and plans... detailed below.

Computing ———

* Frameworks * architecture abstraction * high-level language * DNN integration * Run 3 Framework Core Trigger software (Need to develop) =¿ Great stepping stop to Run 4

* Deep Learning... * Large number of projects built on numerous collaborations =¿ bringing domain/DNN expertise, data, and hardware together. * Enabled by hardware and software tools. =¿ Once setup, subsequent problems are easy to investigate. =¿ Plan: Datasets + Tutorials + HPC

Deep Learning Projects ——————-

1. DNN Matrix Element (w/ Tancredi + Hussien, Tobias Golling + group). =¿ Application: =¿ Encapsulation of LO, NLO, NNLO weights =¿ address NLO generation problem =¿ Encapsulation of MEM =¿ Faster MEM/more sensitive searches =¿ Status: =¿ DNN setup and running, prelim results. =¿ First studies already done on Titan with help of Sergey Patinkin (sp?) =¿ Regression vs binning/classification =¿ Plot: Residual =¿ Plans: =¿ Paper with Tancredi (+ Hussien?) =¿ Paper with Toby =¿ Learned Binning

2. LArTPC DNN Reconstruction (2 Collaborations: Sepideth, Grayson, P. Baldi, P. Sawdosky and UCI group. Asaadi's group) =¿ Application: =¿ Convolutional Nets: =¿ Particle ID =¿ Energy Regression =¿ Neutrino Reconstruction (ID+Energy) =¿ Compliment to Reco: e.g. EM/Had Hit ID =¿ Auto-encoders =¿ Noise suppression =¿ Compression =¿ Status: =¿ Huge dataset Simulated LArIAT DataSet (15M): single particle + neutrino. Just finished! =¿ Many very promising preliminary results. =¿ Best electron versus pi0 separation (compare to MicroBooNE) =¿ Electron and Muon Regression =¿ Optimization going on now =¿ Plans: =¿ Paper with UCI =¿ With Asaadi+Student =¿ Implement technique within LArIAT =¿ Train/Validate on Data =¿ MicroBooNE: Some Neutrino x-section measurement (conventional and DNN) =¿ Ultimately, full DNN-based LArTPC reconstruction/physics. =¿ DUNE Detector Optimization =¿ All LArTPC Experiments...

3. NEXT DNN Reconstruction (nu-less double beta-decay) (J. Renner et al, Nygren/Jones group) =¿ Application (mostly CNNs): =¿ Full Reconstruction... ultimate goal? Can we trust it? =¿ Detector Optimization: =¿ Fast design -¿ simulate =¿ optimized reco cycle (also good idea for DUNE). =¿ Turn on effects in simulation =¿ understand relative impact =¿ Novel searches: =¿ Vertex and trajectory reconstuction =¿ Ben's Lorentz Invariance Test idea (is it a secret?) =¿ Status: =¿ Paper soon: First studies demonstration many of above with out-of-box CNNs. =¿ New collaboration with Ben, Austin, and Ben's new student =¿ Plans: =¿ All of above!

4. Calorimetry (w/ J.R. Vlimant, M. Pierini, ...) =¿ ATLAS Combined performance contribution =¿ Motivation: =¿ 3D Image: Ideally suited... extension of LArTPC work. =¿ Many handles not used =¿ e.g. Accordian shape =¿ e.g. Hadronic Sampling =¿ Potential for Big Impact: =¿ Better PID and Resolution =¿ Bigger peaks =¿ Smaller systematics =¿ Fast Shower: Generative Models =¿ Status: =¿ Large Dataset generated... more to come. =¿ Already shared with Berkeley vision lab and others... =¿ Start with LCD dataset. =¿ First classification results ready... Regression setup. =¿ Paper draft started =¿ Plans: =¿ AF Focus on Energy Regression (same as LArTPC) =¿ Likelihood-based =¿ Generative Models =¿ ATLAS =¿ Changing Granularity =¿ Z data fit (w/ collaborator...)

5. New Physics Searches (w/ Chris Rogan, Paul Jackson, Louise, Daniel, next postdoc ...) =¿ bb ll + MET Topological search: =¿ Status: Jigsaw vs 4-vector based DNN study done. =¿ Current: Parameterize Classifier. =¿ Plan: Establish a topological basis for event classification =¿ Stepping stone to General Searches for end of Run 2 =¿ Compressed Spectra =¿ Status: Training DNN on Rogan data to compare with Rogan paper. =¿ Papers, papers!

6. Anomally Detection: (with P. Onyisi at UT?) =¿ Application: =¿ Detector Monitoring (from 35t days) =¿ General Purpose =¿ Status: =¿ Auto-encoder based anomally detector built using synthetic data =¿ Plan: =¿ Get some ATLAS monitoring data... give it a try.

Physics ——- * History: * 3 Razor searches * squark/gluino sub-convenership: David -¿ Louise

* Accomplishments: * ICHEP 0 Lepton + Compressed Spectra w/ JigSaw * Louise sub-convenorship

* Plans: =¿ DNNs =¿ Draw inspiration: Better Jigsaw-like observables? =¿ Background technique: how do you get a sideband? =¿ Compressed Spectra: Paper with Rogan =¿ ll bb + MET =¿ All Hadronic ???

Other —– Louise: Tile performance paper editor Daniel: Tile MobiDAQ + Phase II

Potential Collaborations at UTA ————————————- Kaushik: DNN upgrade to their MVA SUSY search. Haleh: DNN/MEM Charged Higgs searches. Justin: DNN Tau ID/Reco

## PI Summary: Haleh Hadavand

# 1 The ATLAS Experiment

## The ATLAS Experiment

### 1.1 Atlas Subject One (PI: PersonOne, PersonTwo)

### 1.2 Atlas Subject Two (PI: PersonOne, PersonTwo)

#### 1.2.1 Atlas Sub-Subject (PI: PersonOne, PersonTwo)

# 2 International Linear Collider Project (PI: White)

## ILC Experiment

# Part III
# Research at the Intensity Frontier

**Executive Summary**

The Intensity Frontier group of the University of Texas at Arlington started in 2014 with 0.5 FTE of PI Jae Yu and PI Amir Farbin aiming for a balanced program between US-based and non-US based experiments. Aiming to build a strong Intensity Frontier program, the group recently hired full time Intensity Frontier junior faculty, Dr. Jonathan Asaadi.

While PI Farbin has decided to transition back to EF, since PI Yu is transitioning full time into the Intensity Frontier program, the group now has 2 FTEs consisting of two full time faculty members.

In addition to adding a new faculty member to strengthen the program, UTA IF group has made significant contributions to LArIAT, LBNE and MiniBooNE experiments. Yu has served as a co-convener for the LBNE R&D Coordination group to organize the detector R&D efforts in an effective fashion and has been serving as a co-convener of the DUNE Beyond the Standard Model physics group since September 2015. Yu has hosted the first off-fermilab site DUNE collaboration meeting on the campus of UTA in January, 2016, in which over 150 collaborators participated in. Yu applied for a sabbatical leave and stayed at CERN from late September 2015 through mid May, 2016, during which time he had contributed to WA105 small ($3 \times 1 \times 1\ \mathrm{m}^3$) prototype construction and understanding the behavior of the membrane cryostat. He also led UTAs joining WA104, ICARUS in order to prepare for intermediate physics outcome, and is serving at the institutional representative for the group.

In this proposal, we propose to contribute to MiniBooNE (Yu), LArIAT (Asaadi, Yu). MicroBooNE (Asaadi), SBND (Asaadi, Yu), ICARUS (Asaadi, Yu) and the Deep Underground Neutrino Experiment, DUNE (Asaadi, Yu), including protoDUNE. These experiments are strategically selected to provide our group an advantage of applying a technical advancement from one experiment to another since they all use LAr TPC technology. The work on MiniBooNE, which is limited to data analysis for low mass dark matter detection feasibility to complete shortly with the graduation of Sepideh Shahsavarani, Farbins Ph.D. student, who will stay on the Intensity Frontier program for another two years till she completes her Ph.D. program. We anticipate the data taking and analysis work we have been involved in LArIAT would wrap up as the experiment completes within the next 1 2 year time scale. This will allow us to focus on the SBN experiments and DUNE.

Asaadi is playing a leading role in the operations of MicroBooNE experiment. Asaadi and Yu will play key roles in the construction, commissioning, and operation of SBND through contributions to cold electronics testing, APA assembly, and operations of the detector. These efforts build on our experience in commissioning of the LArIAT and MicroBooNE experiments. UTA is actively involved in the ICARUS experiment where Yu is currently the IB representative and a postdoc is helping the refurbishment of the light detectors at CERN. UTA is also playing key roles in the construction of protoDUNE detectors, template DUNE far detectors. Asaadi is involved in quality assurance and construction of the single phase (SP) protoDUNE. Yu is leading the DUNE BSM physics group and is involved in design and construction of dual phase protoDUNE field cage whose design shares large portion of the SP protoDUNE field cage. These activities aim to ensure synergy between the SBN and LBN efforts and an optimized use of resources.

### 2.0.1 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 ($\nu_e, \nu_\mu, \nu_\tau$) are a linear combination of the neutrino mass eigenstates ($\nu_1, \nu_2, \nu_3$). 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 $\delta$ which determines magnitude of charge-parity (CP) violation within the neutrino sector. Additionally, the flavor change of the neutrinos depends on the ratio 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 $\Delta m^2_{ji}$. 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 $\delta$ 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 ($\Delta m^2_{new} \geq 0.1 eV^2$) 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. 2.

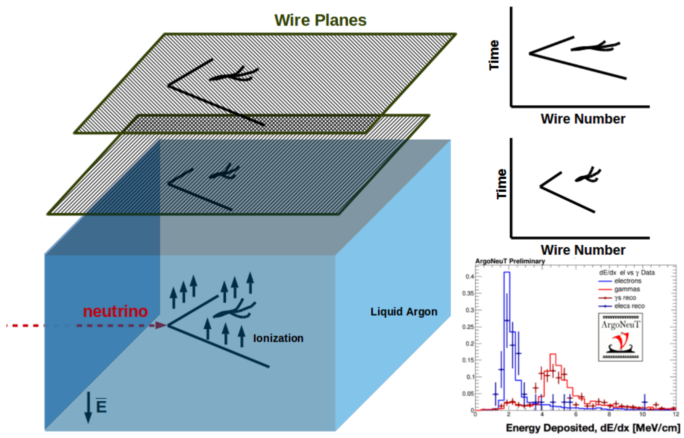


Figure 1: Operating principals of LArTPC detectors.

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.

The UTA intensity frontier group has grown recently with the addition of a junior faculty member, Jonathan Asaadi,and the complete transition of senior faculty Jaehoon Yu to the intensity frontier effort. 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. A summary of the experiments, projects and PI's responsibilities is provided in Table **??**. The details of these projects are given in the subsequent sections.

DUNE (Asaadi, Yu) 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) (Asaadi, Yu), the Micro-Booster Neutrino Experiment (Asaadi), and the ICARUS Experiment (Asaadi, Yu). All three of these SBN experiments as well as DUNE are strategically selected to leverage the UTA expertise in LArTPC technology across them. Asaadi is playing a leading role in the operations of MicroBooNE experiment. Asaadi and Yu will play key roles in the construction, commissioning, and operation of SBND through contributions to cold electronics testing, APA assembly, and operations of the detector. These efforts build on our experience in

**IF Summary of Proposed Work**

| Experiment | Project | Description | Lead PI |
|---|---|---|---|
| SBND | Vertical Slice Test-Stand | Say things here | Asaadi |
| | Detector Construction, Installation, and Commissioning | Details | Yu |
| | High-statistics cross-section | Details | Asaadi |
| MicroBooNE | TPC Detector Expert | Say things here | Asaadi |
| | Coherent Charged Pion Cross-Section | Details | Asaadi |
| ICARUS | Detector Installation and Commissioning | Details | Asaadi |
| | NuMI Off-Axis Cross-Sections | Details | Yu |
| DUNE | protoDUNE Single Phase APA QA/QC and installation | Details | Asaadi |
| | BSM Physics | Details | Yu |
| | protoDUNE Dual Phase FC Construction | details | Yu |
| MiniBooNE | Beam Dump Dark Matter Search | details | Yu |

Table 1: Overview of the UTA projects across the Intensity Frontier

commissioning of the LArIAT and MicroBooNE experiments. UTA is actively involved in the ICARUS experiment where Yu is currently the IB representative and a post-doc is helping the refurbishment of the light detectors at CERN. UTA is also playing key roles in the construction of protoDUNE detectors, template DUNE far detectors. Asaadi is involved in quality assurance and construction of the single phase (SP) protoDUNE. Yu is leading the DUNE BSM physics group and is involved in design and construction of dual phase protoDUNE field cage whose design shares large portion of the SP protoDUNE field cage. These activities aim to ensure synergy between the SBN and LBN efforts and an optimized use of resources.

## PI Summary: Jaehoon Yu

## PI Summary: Jonathan Asaadi

# 3 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. 3, 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.

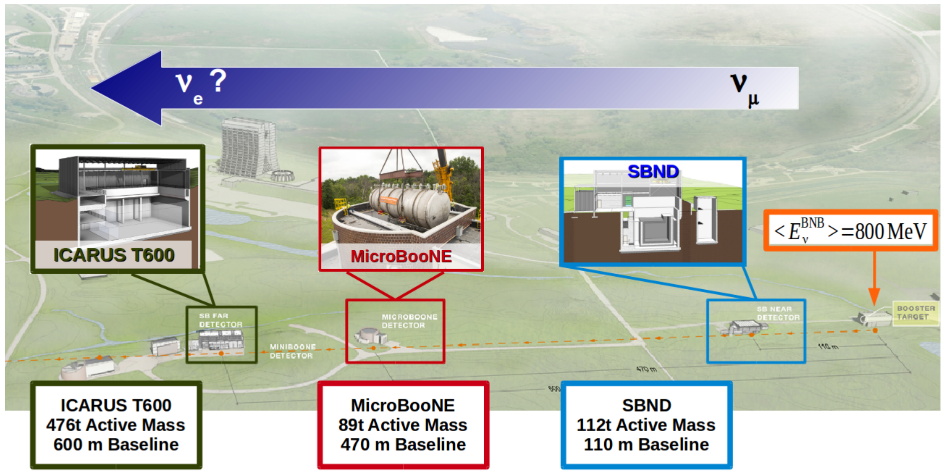


Figure 2: Overview of Fermilab's Booster Neutrino Beamline (orange dashed line) campus with the location and description of the three SBN detectors.

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 3.8$\sigma$ evidence for $\bar{\nu_\mu} \rightarrow \bar{\nu_e}$ oscillations occurring with a $\Delta m^2$ of $\sim$ 1eV$^2$. This suggests an oscillation beyond the SM three flavor neutrino oscillation which occurs at an $L/E_\nu \sim$ 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 $L/E_\nu$ to LSND). MiniBooNE identified muon and electron neutrino interactions by their characteristic Cherenkov rings inside a scintillator detector. As shown in Figure 1, in ten years of data taking in both neutrino and anti-neutrino running MiniBooNE observed a 3.5$\sigma$ excess in $\nu_e$ candidates and a 2.8$\sigma$ excess in $\bar{\nu}_e$ candidates. This excess of events observed by MiniBooNE can be due to electrons from $\nu_e$ interactions as well as from single photon backgrounds, since these two final states are indistinguishable to the Cherenkov imaging detector.

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 $\nu_\mu$ and neutral current disappearance data [?, ?] leads to significant tension between the $\nu_e$ appearance data and the $\nu_\mu$ 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.

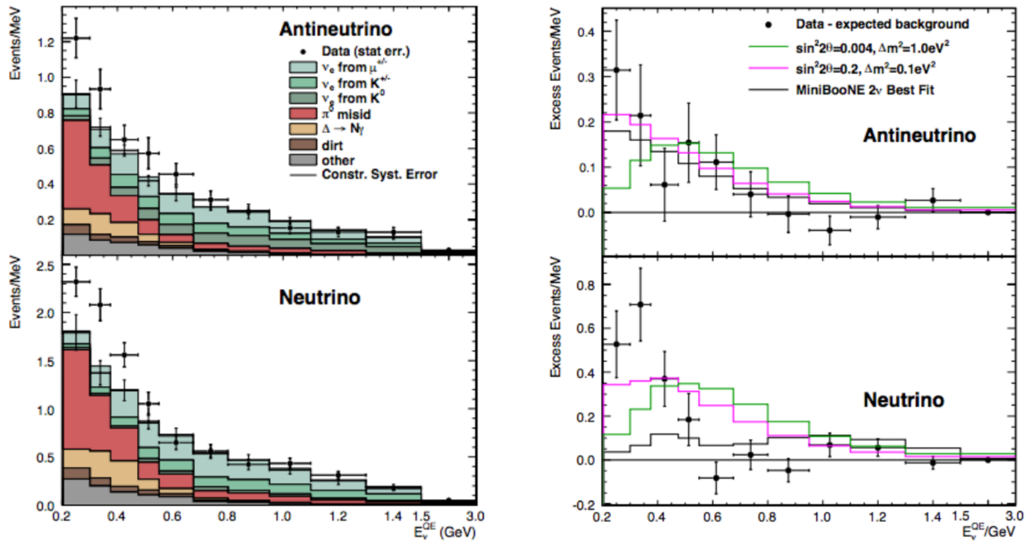


Figure 3: Left: Electron anti-neutrino ($\bar{\nu_e}$) and neutrino ($\nu_e$) candidate events shown with the predicted backgrounds in MiniBooNE. Right: Background subtracted event rates in MiniBooNE as well as different sterile neutrino models overlayed with the data.

### 3.1 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 $\times$ 4.0 m $\times$ 4.0 m (l$\times$w$\times$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.

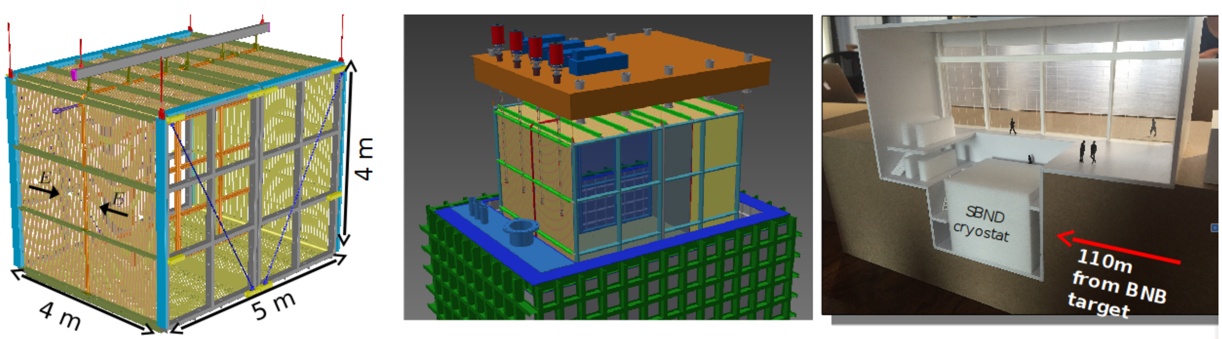


Figure 4: Conceptual design of the SBND TPC, cryostat, and detector hall.

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 performed and serves as an absolutely necessary service task the UTA group is planning to spearhead.

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 $2.2\times10^{20}$ protons on target (roughly one year of running). With 1.5 million $\nu_\mu$ charged current interactions and 12,000 $\nu_e$ charged current interactions in one year. Furthermore, by collecting approximately 100,000 NC$\pi^0$ 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.

The UT Arlington group is positioned to play a major role in the construction and commissioning of the ICARUS and SBND data acquisition system. Leveraging the work on the readout of the ICARUS-CRT positions Prof. Asaadi's group to contribute to the ICARUS and SBND DAQ system. One path to this development is to have the postdoctoral researcher and graduate student supported by this project work to build a vertical slice test-stand for the ICARUS and SBND electronics and DAQ development. 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. Inside this cryostat, a small scale TPC equipped with either prototype cold readout electronics from SBND or the warm electronics for ICARUS 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 or a 14" warm feedthrough as designed for the ICARUS detector. External to the cryostat, scintillator paddles can be positioned to act as both an external trigger as well as provide a proxy for the Cosmic Ray Tagger (CRT) system to be deployed around the SBND/ICARUS cryostat. This test stand is designed to allow for either the ICARUS or SBND readout system to be installed and operated and then swapped for one another. This would allow both short-term integration tests as well as longer term development. The material funds requested in this proposal would go towards the building of the small TPC and light collection system as well as associated cabling. Additional material costs, such as the electronics, power supplies, and feedthroughs are expected to be provided by SBND/ICARUS project funds and Prof. Asaadi's start-up funds.

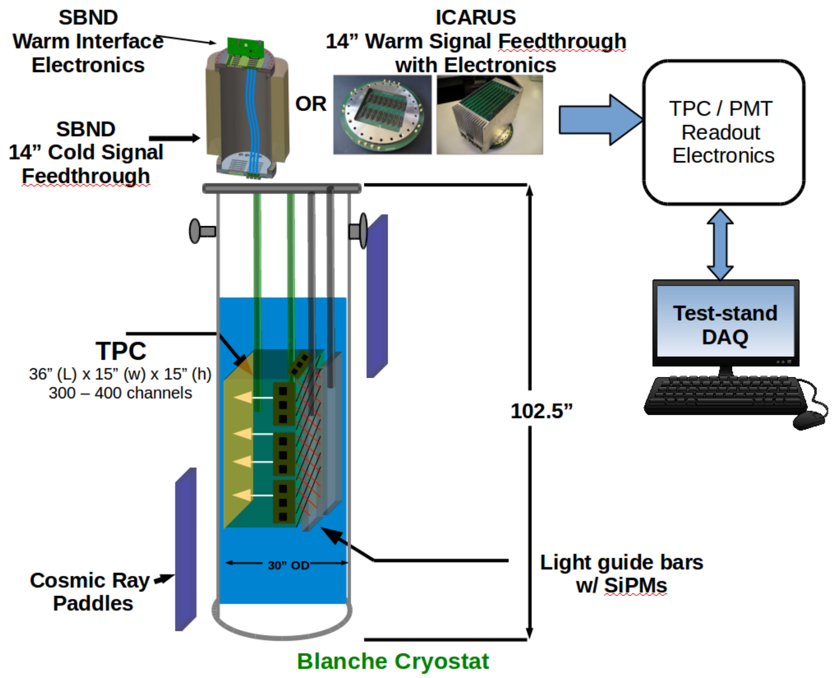


Figure 5: Conceptual design of the ICARUS/SBND vertical slice test-stand. Integration of both cold or warm electronics, light collection system, cosmic ray paddles, as well as warm interface electronics allows for complete testing of the entire readout system prior to deployment in the experiment and a platform for DAQ debugging and development without risk to the experiment. The modular design allows for different readout flanges to be installed and electronics on the TPC to be swapped out based on the necessary testing underway.

With a complete vertical slice of the detector readout, 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 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 ICARUS or SBND experiment.

Furthermore this test-stand will begin the effort to integrate the electronics readout into a common DAQ software package will allow the other SBN LArTPC based experiments to benefit form the work being done. One such framework, known as artDAQ, is envisioned to be used for the SBND experiment and could be expanded to the ICARUS DAQ. The postdoctoral researcher and graduate student supported by this work will be developing the readout software in the artDAQ framework for both the planned test-stand as well as the ICARUS and SBND experiment. 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.

#### 3.1.1 Broader Impact of the TPC/DAQ Teststand

The TPC/DAQ test-stand proposed here is meant to be designed with the flexibility to be used by multiple LArTPC experiments including ICARUS and SBND. This test-stand will 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. These 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.

### 3.2 Micro-Booster Neutrino Experiment (MicroBooNE) (PI: Asaadi)

## MicroBooNE

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 4, has three instrumented wire planes with the first two induction planes oriented at $\pm 30°$ 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 6: The MicroBooNE TPC after installation inside the cryostat and a 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.

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. Figure **??** shows some of the first cosmic ray tracks as seen by the collection plane and the light readout as seen by the PMT system. With the rapid success of the system, MicroBooNE has now transitioned from commissioning to neutrino data taking starting in October of 2015.

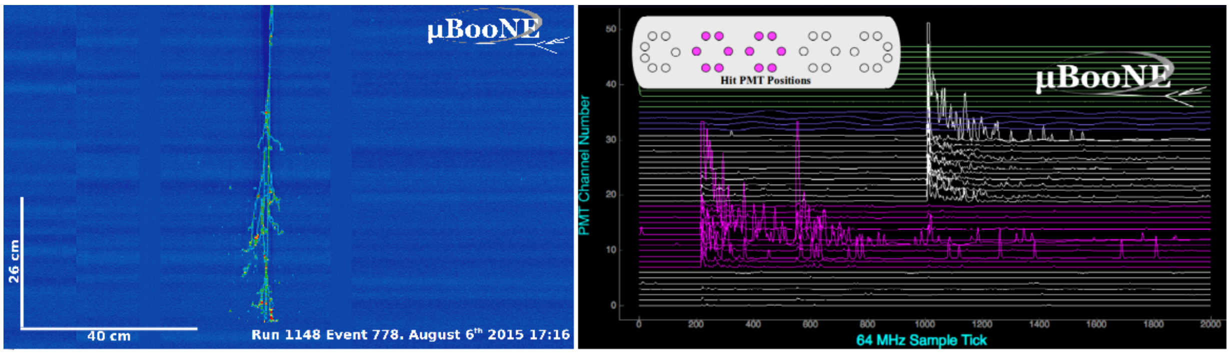


Figure 7: MicroBooNE's first cosmic ray events as seen by the TPC collection plane and the PMT readout.

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 of neutral current $\pi^0$ production can be eliminated using the powerful imaging techniques of a LArTPC. The analysis techniques developed for the MiniBooNE 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.

MicroBooNE will also 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. While MicroBooNE is too small and located on the surface making meaningful proton decay search impossible. However, utilizing the abundance of cosmic rays to search for background signatures due to cosmogenic sources can provide useful input to future analysis targeted at the Deep Underground Neutrino Experiment (DUNE). Additionally, Prof. Asaadi serves as the convener of the Astro-Particle and Exotics working group on MicroBooNE and is currently leading analyses related to proton decay backgrounds and exotic dark matter searches at a beam dump. Fully exploring the physics capabilities of the MicroBooNE detector enables a robust physics program.

### 3.2.1 Proposed work on MicroBooNE

UT Arlington will play a major role in the data taking and operations of the MicroBooNE detector. Prof. Asaadi has served as the TPC commissioning leader and is now transitioning to the TPC operations expert. Prof. Asaadi will also continue in his role as Astro-Particle and Exotics working group convener for the foreseeable future where he will continue to shape the early data analyses as well as explore new physics opportunities with the MicroBooNE detector.

The postdoctoral researcher supported by this proposal will spend much of their time working on the MicroBooNE operations and is expected to be trained to serve as the TPC operations expert. 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. The graduate student supported by this work is also expected to take shifts on MicroBooNE and play a supporting role on the expert training.

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 year of running. This data set will provide the first high statistics glimpse into the short-baseline analysis. Following up on previous low statistics cross-sections measured by ArgoNeuT including the coherent charged pion production and neutral current $\pi^0$ is one way which they can have immediate impact. Furthermore, the tools developed for data analysis and reconstruction in MicroBooNE will have transferability to future LArTPC through the use of the common software package, LArSoft. Neutrino cross-section analysis

## 3.3 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 $8.6 \times 10^{19}$ protons-on-target. The successful operation of a large LArTPC experiment in an underground facility with $> 90\%$ data taking efficiency (collecting ∼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 × 1.5 m ×3.2 m (l×w×h). The TPC has three instrumented wire planes with the first two induction planes oriented at $\pm 60^\circ$ 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. An upgraded light detection system is planned to be 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.

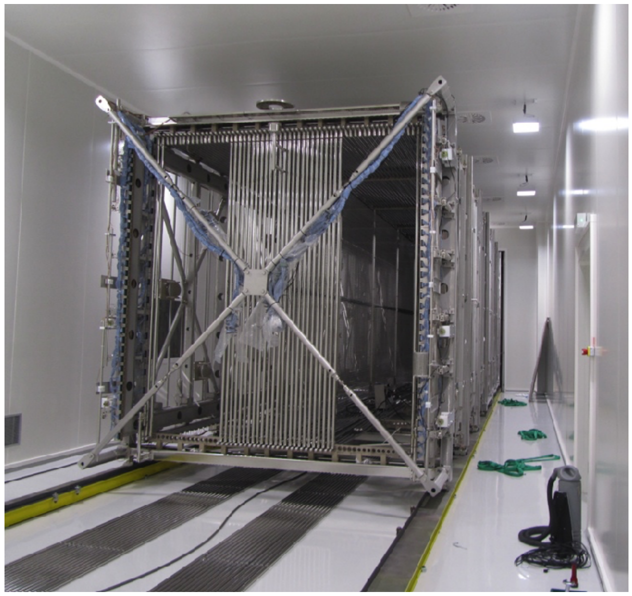

Figure 8: An ICARUS TPC module located at CERN undergoing refurbishment in anticipation of the move to Fermilab in 2017-2018.

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 $\Delta m^2$ (the mass difference between the active and sterile neutrinos) for the simplest 3+1 model. The gray bands represent ranges of $\Delta m^2$ 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 ($5\sigma$) coverage of the LSND allowed region.

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 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 $\pi/\mu$ 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 NC$\pi^0$ 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 $\nu_e$ appearance. ICARUS's large volume ensures near complete photon shower containment and thus increases the statistics available for a NC$\pi^0$ 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.

# 4 The Fermilab Long-Baseline Neutrino Program

## Long-Baseline Neutrino Program

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

## Deep Underground Neutrino Experiment

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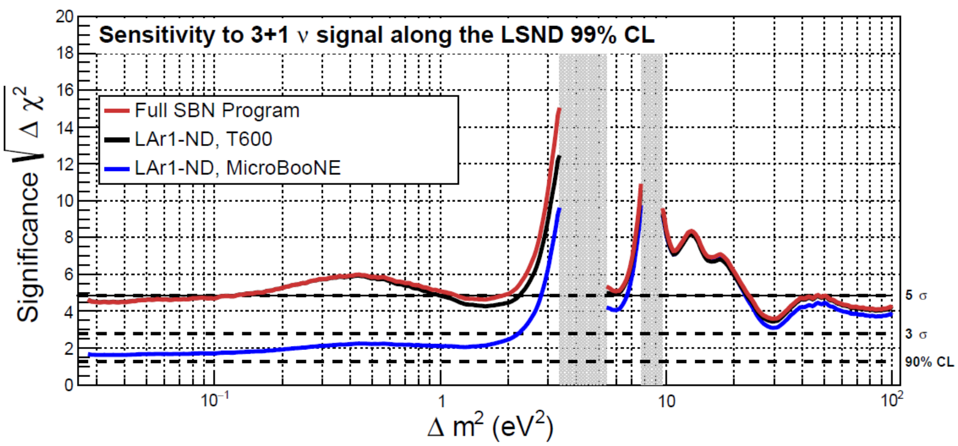


Figure 9: The experimental sensitivity for $\nu_\mu \rightarrow \nu_e$ oscillations including backgrounds and systematics assuming a nominal three year exposure in the BNB for the SBND and ICARUS experiments and a six year exposure for the MicroBooNE experiment.