The Short Baseline Neutrino Oscillation Program at Fermilab

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Outline

- Current state of the field and anomalies
- The SBN program
- Liquid Argon Time Projection Chambers
- Phase I: MicroBooNE
- Phase II: Full SBN (ICARUS and SBND)
- Conclusions
* Established evidence for neutrino flavor oscillations with multiple experiments using different detector technology and neutrino sources

* $\theta_{13}$, mixing angle, opens the way to measurement of $\delta_{CP}$
LSND (Liquid Scintillator Neutrino Detector):

Looking for an electron appearance signal in a $\nu_\mu$ beam.

$\bar{\nu}_\mu \rightarrow e^+$

$E_\nu = 20 - 55$ MeV

Baseline = 30m

One possible interpretation: at least one extra $\nu$ (sterile neutrino ?)
SB Anomalies: MiniBooNE

Excess of low energy electromagnetic events in neutrino and antineutrino mode.

Tension between appearance and disappearance experiments

Same L/E as LSND

SB Anomalies: MiniBooNE

Excess of low energy electromagnetic events in neutrino and antineutrino mode.

At MiniBooNE low energy, $\gamma$ was the biggest background, which was hard to distinguish from $e^{-}$ in Cherenkov detector.
Introducing LArTPC…e/γ Separation

* Can discriminate $e^\pm/\gamma$ with LArTPC
  * Shower displacement from vertex ("gap") for $\gamma$ provides separation
  * Separation with $dE/dx$

Liquid Argon Time Projection Chambers:
* Digitized bubble chamber-like images
* Excellent resolution and Calorimetry
* Scalability to large mass

ArgoNeuT
* Simulated Electron Candidates
* Simulated Gammas
* Electrons, Data
* Photons, Data

Greater ionization density at beginning of γ-induced showers

**ArnoNeuT**
*Phys. Rev. D95, 072005 (2017)*
LArTPC Signal Formation

- Fine grained 3D tracking
- Fully active calorimetry
SBN Program: three LArTPC detectors

Linac
- Length: 150m
- Proton Energy: 400 MeV

Booster
- Circumference: 468m
- Proton Energy: 8 GeV

BNB
- 476 tons
- 85 tons

NuMI
- 470 m

ICARUS-T600
- 470 m

MicroBooNE
- 110 m
- 112 tons

Short Baseline Near Detector (SBND)
SBN Program Goals

* Resolve the “low-energy excess” anomaly
  - Confirm the MiniBooNE result by repeating measurement at similar location, same beam and similar baselines
  - Determine if the excess is electron-like or photon-like in nature

* Search for $\nu_e$ appearance and $\nu_\mu$ disappearance
  - Multiple detectors at different baselines reduce systematics uncertainties with same target and same beam

* Lay groundwork for future long-baseline program
  - Further develop Liquid Argon TPC detector technology
  - Measure $\nu$-Ar cross sections at energies relevant to DUNE
**Phase I: The MicroBooNE detector**

First detector to come online from the SBN Program  
Running Stably since 2015!

* Liquid Argon Time Projection Chamber:
  - Three planes of wire at 3mm pitch
    - One Collection plane at $0^\circ$ from vertical
    - Two induction planes at $\pm 60^\circ$
  - Total 8192 channels
  - 2.5 m drift length

* Optical System:
  - 32 cryogenic photomultiplier tubes (PMT)
  - LED based light injection system

* UV Laser Calibration System

* External Muon Tagger System

* 170 tons of purified LAr  
  (active mass ~85 tons)
Detector Performance & Stability

- High DAQ uptime - greater than 97% POT-weighted DAQ uptime on average
- Electron lifetime is very high (steadily above 6 ms), measured by purity monitors as the fraction of charge detected at its anode relative to its cathode

MicroBooNE-NOTE-1003-PUB.pdf
Active Detector Physics Program

* Develop foundational knowledge of LArTPC design, capabilities, and operation
  
  - Essential for SBN and DUNE
  - Purity, Noise studies, wire response, energy scale, cosmic ray rate, space charge effects, e\(^{-}\) lifetime, diffusion etc.
Active Detector Physics Program

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Many new results will be shown in next talk - Chris Barnes
Developing LAr Reconstruction

Pandora

Simulated BNB $\nu_\mu$ CC interactions

Tagging using an external counter

MicroBooNE Simulation

$\nu_\mu + Ar \rightarrow \mu^- + p + \pi^+$

JINST 12, P12030 (2017)

Data - stat. @ sys.
Data - stat. only
Monte Carlo

Data/MC
Standard Candle: Michel Electrons

Tons of cosmic data available due to the detector being at the surface!

* Ideal to study detector’s response to electrons in the tens of MeV energy scale and further develop reconstruction
* Michel electron identified by Bragg peak and kink in the track
* Preliminary calibration using stopping muons depositing known dE/dx
* Missing energy from radiated photons accounts for spectral distortions
Many physics results are coming out:

- First $\nu_\mu$ CC Inclusive differential cross-section
- First $\nu_\mu$ CCE$^0$ cross-section
- Single photon LEE search
- Updated charged particle multiplicity
- And more! - **12 New Public Notes**
Phase II: ICARUS - the far detector

* High sensitivity to neutrino oscillation effects given its large mass and relatively large distance from the source
* ICARUS underwent refurbishment at CERN after operation at Gran Sasso
  - Updated PMTs and electronics
  - Cathode plane smoothing
  - Recirculation/purification
* Detector arrived at Fermilab last summer
* Currently in installation phase
  - Expecting commissioning in early 2019
**Phase II: SBND - the near detector**

* The short baseline near detector will be located closest to the source of neutrinos
  - high statistics flux measurement
  - measure beam neutrino composition before they oscillate
* Completely new detector with new techniques relevant to scaling up to DUNE
  - four APA and 2 CPA assemblies
  - cold readout electronics
* Detector design finalized and under construction
* Expecting first data in 2020
Phase II: Full SBN Running

* Three-detector combined fit: SBND provides flux and cross section constraints
  MicroBooNE and ICARUS-T600 provides signal events
* Good energy resolution, small background w/ LArTPCs

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\nu_e \text{ charged-current distributions}
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**LAr1-ND, 6.6e+20 POT (100m)**
- Signal: \( (\Delta m^2 = 0.43 \text{ eV}^2, \sin^2 2\theta_{13} = 0.013) \)
- Statistical Uncertainty Only

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**SBND**

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**T600, 6.6e+20 POT (600m)**
- Signal: \( (\Delta m^2 = 0.43 \text{ eV}^2, \sin^2 2\theta_{13} = 0.013) \)
- Statistical Uncertainty Only

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**ICARUS - T600**

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arxiv:1503.01520
SBN Sensitivity

$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 (1.27 \Delta m_{41}^2 L/E)$

Cover the LSND allowed region at 5$\sigma$

$P_{\mu \mu} = 1 - \sin^2 2\theta_{\mu \mu} \sin^2 (1.27 \Delta m_{41}^2 L/E)$

Search for $\nu_\mu$ disappearance which $\nu_e$ appearance implies
* The SBN program is on track to address the eV-scale sterile neutrino anomalies with $5\sigma$ coverage of LSND signal and best global fits

* MicroBooNE continue to pave the way in understanding how to operate, calibrate, and perform physics analyses with LArTPCs
  - Many new physics results coming out next week!
  - Advancing LArTPC technology for future multi-kiloton detectors

* ICARUS and SBND will come online in next two years

Thanks for your attention!
Back-Up
LArTPC Principle

- Ionization from neutrino interaction drifts past two **induction** planes (U, V) and collected on **collection** plane (Y) – three planes in total
  * High drift E field (~500 V/cm), ~uniform via surrounding field cage
  * Front-end electronics in liquid argon to reduce noise levels
- 3D event reconstruction by combining signals from all three planes
- Trigger event with scintillation light from PMTs (or similar)
MicroBooNE Timeline

December, 2013
TPC inserted into Cryostat

June, 2014
Moved to LArTF

July, 2015
Fill with 170 ton LAr

August, 2015
First Cosmic tracks with HV

October, 2015
First Neutrino Beam

November, 2015
First Public Result
Selected Events

Fully Contained $\nu_\mu$ CC event

Partially Contained $\nu_\mu$ CC event

BEE Link