Exciting time to be working on SBN

After Neutrino 18, the goals of Short Baseline Neutrino (SBN) program continue to be very relevant to the field

• Investigation of the sterile neutrino anomaly

  • New results from $\nu_e$-appearance and $\bar{\nu}_e$-disappearance do not yet exclude the global best fit

  • Strong tension remains between channels, especially with $\nu_\mu$-disappearance

• Help further understanding of argon-nucleus cross sections

• R&D in hardware, reconstruction, calibration, data analysis techniques for LArTPCs relevant for future LArTPC experiments like DUNE
Outline

- Brief overview of the Short Baseline Neutrino program
- Status of ICARUS/SBND
- Focus will be on recent results from MicroBooNE, the first detector to be taking data
Three LArTPCs in the BNB

SBN Program

MicroBooNE and the future SBN program

The Short-Baseline Neutrino Program

A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

SBND

MicroBooNE

ICARUS

Booster Neutrino Beam

ICARUS

MicroBooNE

SBND

L = 600 m
M = 476 ton

L = 470 m
M = 85 ton

L = 110 m
M = 112 ton

Taritree Wongjirad

SBN w/ UB Results: 2018 Users Meeting
The Booster Neutrino Beam (BNB) Flux

absolute flux through MicroBooNE active volume TPC

- BNB flux has a lower energy relative to NuMI
- Average 800 MeV
- Intrinsic $\nu_e$ about 0.5%

from Public Note: MicroBooNE-1031-PUB
LArTPCs

How to build and operate a liquid argon time-projection chamber
LArTPC Operation

Start with cryostat filled w/ LAr

Inside protoDUNE cryostat, similar to what will be used for SBND

LAr

Cross section view (w/ beam going into the slide)
LArTPC Operation

Insert a TPC

Cathode (-)

Anode

wire planes (+)

SBND using the DUNE TPC design

inside uB TPC during assembly

cathode

anode

inside ICARUS T600 TPC

Cathode
LArTPC Operation

Anode consists of several charge-sensitive sense-wires

Three Wire Planes
(using MicroBooNE as example)

\[ U \text{ plane (induction)} \oplus V \text{ plane (induction)} \oplus Y \text{ plane (collection)} = \]

8256 wires

pitch = 3mm
LArTPC Operation

interaction produces charged particles
LArTPC Operation

liberates ionization electrons
(and argon ions, not shown)

deposited energy also produces scintillation photons
(not shown in cartoon)

within nanoseconds photons collected by detectors placed behind the anode wires

light signal important for timing
LArTPC Operation

ionization follows field to anode
LArTPC Operation

drift is relatively slow (e.g. ~2.3 ms from cathode to anode in uB)

during that time cosmic particles, mainly muons, will also create tracks of ionization
LArTPC Operation

ionization drifts past (induction) or collects on (collection) wire planes. each provides 2D view of same event
The SBN program

• Program proceeding in two stages

• MicroBooNE (phase 1) investigation of MiniBooNE anomaly
  • Currently taking data
  • Search for presence (or not) of excess
  • Is it electron-like or photon-like?

• ICARUS/SBND (phase 2) definite search for sterile neutrinos
  where near and far detectors reduce the influence of beam and cross section systematics
**Sensitivity**

- Reach of full program
- SBND/ICARUS (6.6e20 POT ~ 3 years)
- MicroBooNE (13.2e20 POT ~ 6 years)

\[ \nu_\mu \rightarrow \nu_e \] Appearance

\[ \nu_\mu \rightarrow \nu_\mu \] Disappearance

SBN sensitivities assume exposures of:
- 6.60\times10^{20} protons on target in ICARUS and SBND
- 13.2\times10^{20} protons on target in MicroBooNE


Global 2017 best fit

\[ \sin^2 2\theta_{\mu e} \]

\[ \sin^2 2\theta_{\mu \mu} \]

\[ \Delta m^2 (eV^2) \]

\[ \Delta m^2 (eV^2) \]
Status: SBND

- Detector construction underway!
- Planned data taking 2020

**Foils**
- CPA will be fitted with TPB coated reflector foils.
- Shifts UV Ar scintillation light to visible.

**CPA**
- Frame constructed.
- Shipping to Fermilab.

**APA**
- Frames constructed.
- Wiring in progress.

see Tom Brook’s New Perspectives Talk for more info
Status: SBND

- Detector construction underway!
- Planned data taking 2020

**Neutron background**
- Taking measurements with portable liquid scintillator neutron detector.

**CRT**
- Production in full swing.
- Several modules delivered to Fermilab.
- Beam measurements underway in SBND pit.
Status: SBND

- SBND performing R&D with candidate DUNE technologies
- E.g. Photon detection system will test candidate several candidate technologies

**Light bars**
- Acrylic bars dip-coated with TPB coupled to SiPMS.
- Only sensitive to UV.
- Improves tracking.

**PMTs**
- 120 8” Hamamatsu PMTs (96 TPB coated).
- Mounts being fabricated.
- Preparing for full system test.

**ARAPUCAs**
- Trap photons with highly reflective internal surface.
- Detect with SiPMS.
- Prototypes under construction.
Status: ICARUS

- Detector construction underway
- TPC arrived last summer
- Warm vessel completed
- Cold shield recently installed
- Cosmic Ray Tagger being installed and tested
- Detector installation will begin next month (July)
- Data taking planned for 2019!
MicroBooNE Operations

- Detector operating stably
- >95% DAQ up-time
- 9.4E20 POT collected currently

Results shown today from portions of Run 1

smooth and steady data taking

Efficient data acquisition

purity vs. time

Very stable detector operation

11 ms e- lifetime

3 ms e- lifetime

Run 1

Run 2

New service boards

Run 3

Full Cosmic Ray Tagger
Detector Response

- Improvements to noise characterization + filtering plus wire response modeling leading to more accurate MC and measurements of charge deposition in data

A cloud of ionization produces signals on several adjacent wires

Properly accounting for this helps better true position and amount of ionization than past method

Enables accurate calorimetric information in all three planes -- improves induction planes in particular
Reconstruction

- Several independent reconstruction methods taking very different approaches
- Having independent analyses with different code-bases and approaches will provide valuable cross-checks

Starts w/ 2D patterns to get **3D recon.**
Widely used by LArTPC community

Use tomographic approach to turn 2D charge info. into 3D charge. Start w/ 3D earlier

Employ recent computer vision advances


*“Three-dimensional Imaging for LArTPCs”, JINST 13 05 P05032 (2018) Public Note: MICROBOONE-1040-PUB*

*“Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber”, JINST 12, P03011 (2017)*

*“Projection Chamber Neutrino Events in a Liquid Argon Time Projection Chamber”*, JINST 12, P03011 (2017)
Analysis Roadmap

• Employing available reconstructed quantities in a staged manner
  • Locate neutrino vertex and count number of attached charged tracks: first test of interaction and flux models
  • Reconstruct kinematics of individual tracks: inclusive $\nu_\mu$-CC cross section
  • Reconstruct showers associated to inclusive $\nu_\mu$ CC vertices: $\nu_\mu$-CC $\pi^0$ cross section
• Producing physics while building reconstruction and analysis for the low-energy excess search
Charged particle multiplicity

- Our first physics result!
- CPM distribution used to test nuclear models in generator
- Data lower than expectation at high multiplicities

Inclusive $\nu_\mu$-CC Cross section

- inclusive $\nu_\mu$-CC differential cross section
- Comparison to GENIE with different model choices
- First comparisons for Argon at low energies (<1 GeV)

Public Note: MICROBOONE-NOTE-1045-PUB, 2018

Double-differential cross section coming soon!

forward bin a handle for investigating nuclear effects

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^- X$
$\rightarrow$

E_v (GeV)

$\nu_\mu$ N $\rightarrow \mu^+ X$

$\nu_\mu$ N $\rightarrow \mu^- X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^+ X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^- X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^+ X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^- X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^+ X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^- X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^+ X$
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MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^- X$
$\rightarrow$

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MicroBooNE Preliminary

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MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^+ X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^- X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^+ X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^- X$
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MicroBooNE Preliminary

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MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^+ X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^- X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^+ X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^- X$
$\rightarrow$

MicroBooNE Preliminary

$\nu_\mu$ N $\rightarrow \mu^+ X$
$\nu_\mu$-CC $\pi^0$

- Measurement requires crucial components to low-energy excess analysis
  - Shower reconstruction and validation of shower resolution
  - First $\nu_\mu$-CC $\pi^0$ measurement on argon

Flux integrated cross section

$$\left< \sigma^{\nu_\mu CC \pi^0} \right> \phi = (1.94 \pm 0.16 \text{[stat.]} \pm 0.60 \text{syst.}) \times 10^{-38} \text{cm}^2 / \text{Ar}$$

Two-photon invariant mass

Public Note: MICROBOONE-NOTE-1032-PUB, 2018

Next steps: higher statistics analysis leading to differential cross-section
DL on data

- Next-gen. reconstruction tools coming on-line soon from all techniques
- Example: pixel-labeling of MicroBooNE images on data using a deep convolutional neural network
- DL-techniques showing promise for DUNE reconstruction
- MicroBooNE provides the opportunity to establish that these techniques work on LArTPC data, despite being trained on MC

Study on $\nu_\mu$-CC $\pi^0$ data events

- raw image
- human labeled
- machine labeled

Disagreement between human and machine

preliminary: publication coming very soon!
Building to Low Energy Excess

Have built a foundation from which to investigate the excess using different tools and channels.

Such approaches important to test different possible explanations of the excess, not just sterile neutrinos.

These are current analyses, but more to come.

Automated Reconstruction Tools

- Pandora
- Deep Learning
- Wire Cell
- and more...

Calibrations:
- wire response understanding and modeling
- Stable operation of both detector and beam
Summary

• MicroBooNE, the first phase of the SBN program, has built a solid foundation from which it has put out first results with many more on the way

• MicroBooNE has developed our first fully automated nue and single photon selections, some with independent techniques, and are addressing the improvements needed for the low-energy excess search

• SBN progressing towards phase 2: ICARUS and SBND detector construction on-going with full three detector data taking by 2020
Backups
More on MicroBooNE
Building to Low Energy Excess

Taking a blind approach

These tools have been building on a small sample of data which cannot provide significant indication

NuMI sample recorded: provides sample of electron neutrinos to validate with

1\text{\gamma}+1p
1\text{\gamma}+0p
1L+Np
1L+1p
1L incl.

Automated Reconstruction Tools
Pandora
Deep Learning
Wire Cell
and more…

calibrations
wire response understanding and modeling
Stable operation of both detector and beam
Building to Low Energy Excess

Adding Improvements to foundation as well

CRT data will be incorporated to assist in cosmic removal

measurements of space charge will improve current model

Automated Reconstruction Tools

Pandora

Deep Learning

Wire Cell

and more…

cosmic tagging with CRT

space charge measurements/corrections

calibrations

wire response understanding and modeling

Stable operation of both detector and beam
Good wire coverage

All unresponsive wires on all three planes (~10%)

All unresponsive wires with no redundancy (~3%)
Neutrino Interactions with Nucleons

Quasi-elastic (QE)

\[ \nu_\mu \rightarrow W \rightarrow \mu^- + \text{p}^+ \]

Resonance (RES)

\[ \nu_\mu \rightarrow W \rightarrow \pi^+ + \text{n} \]

Deep inelastic (DIS)

\[ \nu_\mu \rightarrow W \rightarrow \mu^- + X \]

\[ 11/5/15 \]

A. Schukraft

Lots of interest in neutrino physics over all energy ranges.

A. Schukraft, G. Zeller

Many open questions need experimental & theoretical input!

The only measurement on argon from ArgoNeuT

\[ \text{Micro BooNE, T2K, DUNE, NOvA} \]

\[ \nu \text{ cross section } / E_\nu \left( 10^{-38} \text{ cm}^2/\text{GeV} \right) \]

\[ 10^{-1} \rightarrow 1 \rightarrow 10^2 \]

E_\nu (GeV)
CCPi0
**FIG. 1:** The $\nu_\mu + Ar \rightarrow \mu + (1\pi^0 \rightarrow \gamma\gamma) + X$ shower reconstruction efficiency as a function of the deposited energy of the shower. Overlaid is the energy distribution of the decay photons from neutrino induced $\pi^0$ in our simulation. The leading shower in red and the subleading shower in blue.

These clusters are compared to the neutrino vertex and if they are not well aligned with it they are rejected. Further, if the cluster appears to be too linear or possibly originating from a track-like particle it is rejected [23]. This procedure will struggle for lower energy EM particles, near the Michel spectrum of around 50 MeV, as these will shower in a more stochastic fashion [24] and appear track-like in our readout. In the second stage of EM shower reconstruction the hits designated as shower-like are passed to a re-clustering procedure that works radially from the candidate neutrino vertex using OpenCV, an open source image processing tool [25 and 26]. During image processing all contiguous hits are formed into a 2D cluster on a given plane. The resulting OpenCV clusters are matched via the time extent of the cluster between the collection plane and one of the two induction planes. With matched clusters, shower properties such as 3D direction and energy from the summed hit charge on the collection plane can be calculated. This shower reconstruction procedure aims to reconstruct photons emanating from neutral pion decays with a clearly defined vertex location.

The algorithm results in highly charge pure showers (on average 92% of the charge comes from the same particle) at the expense of charge completeness (on average 63% of a particles' total charge is collected) which impacts the overall energy resolution.
Collected Neutrino
18 Results
Neutrino 18: Sterile Summary

Summary

- Anomalies in $\nu_e \rightarrow \nu_e$ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance experiments point towards conversion mechanisms beyond the well-established 3$\nu$ oscillation paradigm;
- each of these anomalies can be individually explained by sterile neutrinos;
- sterile neutrinos still succeed in simultaneously explaining groups of anomalies sharing the same oscillation channel. However some problem arises:
  - $\nu_e \rightarrow \nu_e$ disappearance data face issues with flux normalization and the 5 MeV bump, as well as small tensions in reactor vs gallium and “rates” vs DANSS/NEOS;
  - $\nu_\mu \rightarrow \nu_e$ appearance data show an excess in low-E neutrino data, which is not so manifest in antineutrino data.
- in contrast, no anomaly is found in any $\nu_\mu \rightarrow \nu_\mu$ disappearance data set;
  ⇒ sterile neutrino models fail to simultaneously account for all the $\nu_e \rightarrow \nu_e$ data, the $\nu_\mu \rightarrow \nu_e$ data and the $\nu_\mu \rightarrow \nu_\mu$ data. This conclusion is robust;
- if the $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ anomalies are confirmed, and the $\nu_\mu \rightarrow \nu_\mu$ bounds are not refuted, new physics will be needed. Such new physics may well involve extra sterile neutrinos, but together with something else (or some “unusual” neutrino property).

Michele Maltoni <michele.maltoni@csic.es>

Neutrino 2018, 8/06/2018

https://zenodo.org/record/1287015#.WyKcxRJKjOQ
**FIRST RESULTS**

**OSCILLATION SEARCH RESULTS**

\[
\sin^2(2\theta_{14}) 
\]

**PROSPECT Exclusion, 95% CL**

**PROSPECT Sensitivity, 95% CL**

**SBL + Gallium Anomaly (RAA), 95% CL**

**PRELIMINARY**

- **RAA BEST FIT**

- **Disfavors RAA best-fit point at >95% (2.3σ)**

- **Covariance matrices captures all uncertainties and energy/baseline correlations**

- **Critical χ^2 map generated from toy MC using full covariance matrix**

- **95% exclusion curve based on 33 days Reactor On operation**

- **Direct test of the Reactor Antineutrino Anomaly**

**Active-to-sterile oscillation**

- **Normalized with the Daya Bay shape**

- **Best fits at:**

  \[(1.73 \text{ eV}^2, 0.05), (1.30 \text{ eV}^2, 0.04)\]

  \[\chi^2(3\nu) - \chi^2(4\nu) = 6.5, \quad p-value = 0.22\]

- **Fine structures in reactor ν spectrum or oscillation?**

**FIG. S1.** The \(\chi^2\) difference between the 3-ν hypothesis and the best fit for 3+1 hypothesis from 200,000 Monte Carlo (MC) data sets generated based on 3-ν hypothesis with statistical and systematic fluctuations (blue). For the uncertainties of the neutrino flux, the data from Fig. 29 in Ref. [31] are used. The p-value corresponding to \(\Delta\chi^2 = 6.5\) is estimated at 22%. Superimposed is the \(\chi^2\) distribution with two degrees of freedom (green).
Neutrino 18: MINOS+

- Minos & Minos+ data 90% C.L.
- Minos 90% C.L.
- IceCube 90% C.L.
- Super-K 90% C.L.
- CDHS 90% C.L.
- CCFR 90% C.L.
- SciBooNE + MiniBooNE 90% C.L.
- Gariazzo et al. (2016) 90% C.L.
MINIBOONE

EXCESS BACKUPS
MiniBoonE Low Energy Excess

- MiniBooNE saw an excess of (anti-)electron neutrino events at low energy

- Potential explanation:
  - Neutrino oscillations, but at this distance (500 m) incompatible with previous measurements like Super-K
  - possible explanation are *sterile neutrinos!*

MiniBoonE Low Energy Excess

- Other possibilities for the excess
  - due to mis-id backgrounds, such as photons coming from some un-modeled neutrino process
  - Need a detector that can distinguish photon vs. electrons and potentially address these other issues

Photons versus Electrons in LArTPCs

Electron leaves one unit of charge near start of shower

\[ e^- \]

Photon converts (much of the time), leaves two unit of charge

\[ \text{photon} \rightarrow e^- + e^+ \]

Demonstration of handle in the ArgoNeuT Detector

SBN BACKUPS
FIG. 21: Electron neutrino charged-current candidate distributions in LAr1-ND (top), MicroBooNE (middle), and ICARUS-T600 (bottom) shown as a function of reconstructed neutrino energy. All backgrounds are shown. In the left column, only muon proximity and $dE/dx$ cuts have been used to reject cosmogenic background sources. In the right column, a combination of the internal light collection systems and external cosmic tagger systems at each detector are assumed to conservatively identify 95% of the triggers with a cosmic muon in the beam spill time and those events are rejected. Oscillation signal events for the best-fit oscillation parameters from Kopp et al. are indicated by the white histogram on top in each distribution.

Counts listed for Dirt and Cosmogenic events are larger than those given in Sections II F and II G. This is a result of energy smearing effects which are properly simulated in the final sensitivity analysis (15%/pE), but not in the earlier stages of simulations where true energies were used to display the predictions. The predicted background energy spectra are provided well below the 200 MeV cut value used in the analysis such that events can be properly smeared in both directions. Because both backgrounds are steeply falling functions of photon...
Status: SBND

- SBND performing R&D with candidate DUNE technologies
- E.g. Photon detection system will test candidate several candidate technologies
- operating side-by-side
  - PMT system (uB and ICARAUS-like) serves as reference to well-known system
  - Light-guide bars
  - ARAPUCAS
- Reflecting foils to increase light-yield
DL BACKUPS
ConvNets In a Slide

- ConvNets work by finding complex, hierarchal features to represent abstract information in images.
- Begin with image pixels (layer 1).
- Start by applying convolutions of simple patterns (layer 2).
- Find groups of patterns by applying convolution on feature maps (layer 3).
- Repeat.
- Eventually patterns of patterns can be identified as faces (layer 4).