Short-Baseline Liquid Argon Neutrino Experiments

Interdisciplinary Developments in Neutrino Physics Conference
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Outline

Why Short-Baseline* (SBL) Neutrino Experiments?

Beyond three neutrino mixing & alternative physics scenarios.

Why Beyond Standard Model in SBL Liquid Argon Time Projection Chamber Neutrino Experiments?

**MicroBooNE**: first low energy excess result.

**ArgoNeuT**: constraints on new physics in unexplored parameter space regions.

Short-Baseline Neutrino program: sterile neutrinos & other BSM explorations and neutrino interaction measurements.

*Short-Baseline: $L \sim 100-1000 \text{ m}$, $L/E \sim 1\text{ eV}^2$, to be compared with Long-Baseline: $L \sim 100-1000 \text{ Km}$, $L/E \sim 10^{-3}\text{eV}^2$*
Short-Baseline Neutrino Anomalies

Accelerator “anomalies” (LNSD and MiniBooNE experiments) + Reactor and Gallium “anomalies”

could be pointing at BSM physics in the neutrino sector:
additional “sterile” neutrino state(s) with large mass-squared differences,
driving neutrino oscillation at small distances.

Beyond Three Neutrino Mixing?
Why Short-Baseline Neutrino Experiments?

Mainly:

Various hints of anomalous electron-flavor appearance and disappearance may be indicative of new neutrinos participating in oscillations (eV-scale sterile neutrinos)

and also

Neutrino cross sections measurements for understanding neutrino interaction with matter and informing oscillation measurements.

But it is an evolving landscape

Alternative potential explanations from more recently emerging new physics scenarios from theory.
The parameter space of new oscillations/interactions continues to be explored with accelerator-based, including decay-in-flight and decay-at-rest, and reactor-based SBL experiments.*

Here will focus on recent results and status of accelerator-based (decay-in-flight) Liquid Argon Time Projection Chamber (LAr TPC) experiments:

- Short-baseline Neutrino (SBN) program and ArgoNeuT experiment at Fermilab.

*See C. Giunti, T. Lasserre, arXiv:1901.08330 for a review on eV-scale sterile neutrinos, including a complete list of current/future experiments (accelerator- and reactor-based experiments). See presentation from K. Heeger at this conference (on Wednesday), for a review of SBL reactor experiments.
Why BSM in SBL LAr TPC Neutrino Experiments?

The combination of
- **High-intensity proton beams (high intensity neutrino beams)** coupled with
- **Large mass LAr TPC detectors** close to the beam target, with
  - Event imaging
  - Fine granularity calorimetry and particle identification
  - Good timing resolution
  - Low energy threshold

**opens up unprecedented opportunities to probe signatures for**

**New Physics scenarios in the neutrino sector and beyond**

- **Modifications to the neutrino oscillation paradigm** (effects of BSM physics on neutrino oscillation)
- **Novel experimental signatures** produced in the beam target
Why Liquid Argon Time Projection Chamber?

LAr TPC: Bubble chamber quality of data with added calorimetry

Liquid argon is the technology of choice for precision neutrino physics.
The LAr TPC Technology

Measure neutrino interactions in real time with millimeter position resolution. Excellent capability for energy depositions from sub-MeV to few GeV, far beyond that offered by any other neutrino detector.

LArTPC at work: imagining, energy and timing

- Multiple 2D and the 3D reconstruction of charged particles ⇒ Imaging
- Total charge proportional to the deposited energy ⇒ Calorimetry
- dE/dx along the track ⇒ Particle Identification

and few ns **timing** resolution from light detection system(s).
From “easy” to progressively more complicated topologies...

Characterize events in terms of particle content and kinematics
Electrons or photons?

MiniBooNE electron-like "Low Energy excess"… Photons? Electrons?

LAr TPC!
Electron-$\gamma$ discrimination in LAr TPC

Analyzing topology (gap from the vertex) and $dE/dx$

- e-$\gamma$ discrimination capability of LAr is crucial to disentangle the signal/background nature of the electron-like excess observed by MiniBooNE
The capability to resolve individual collisions down to < MeV threshold is important for

- Neutrino Energy reconstruction [A. Friedland and S. Weishi Li, PRD 99, 036009 (2019)]
- Detection and reconstruction of supernova neutrino interactions in large LArTPCs (ex. DUNE)
- Study new physics scenarios
Short-Baseline LAr TPC detectors at Fermilab: ArgoNeuT

First LAr TPC detector at FNAL
5 months data collected in 2009-2010

On-axis on NuMI \(<E_\nu> = 4\) GeV

0.24 tons active volume LAr TPC
100 m underground, in front of the MINOS ND, ~1km from target
World’s longest running LAr TPC (2015-2021)

On-axis on BNB ($<E_\nu> \approx 800$ MeV) and off-axis on NuMI
Two other detectors to form the Short-Baseline Neutrino (SBN) program

On-axis on BNB (SBND, MicroBooNE, ICARUS) and off-axis on NuMI (MicroBooNE, ICARUS)
Short Baseline Neutrino program

Designed for Sterile Neutrino searches
Same neutrino beam, nuclear target and detector technology:
reducing systematic uncertainties to the % level

*arXiv:1503.01520, January 2014*

MicroBooNE experiment

- Designed to investigate the “low energy excess” observed by the MiniBooNE experiment.
- Physics run completed in 2021.
- First results on the “low energy excess” have been recently released (~1/2 of the full data sample). Four independent analyses, targeting different final states:
  - Single photon analysis
  - Search for a $\nu_e$ excess

**Single photon**

No evidence for an enhanced rate of single photons from $\text{NC} \Delta \rightarrow \text{N} \gamma$ decay above nominal GENIE expectations

*P. Abratenko et al., PRL 111801 (2022)*
Search for a $\nu_e$ excess

Three independent reconstruction frameworks.

P. Abratenko et al., arxiv:2110.14054 (2021)
Search for a $\nu_e$ excess

Observed $\nu_e$ candidate event rates in agreement with, or below, the predicted rates.

Reject the hypothesis that $\nu_e$ CC interactions are fully responsible for the MiniBooNE excess at >97% C.L. in all analyses.

Currently planning the next phase of analyses.
Neutrino data taking (BNB and NuMI) since October 2021

Commissioning of the full Cosmic Ray Tagger system and installation of a concrete overburden is ongoing.
SBN Near detector: SBND

TPC assembly almost completed
Warm outer vessel installed in the building
Cryogenics/cryostat installation in progress
Ready for cold commissioning by Spring 2023

TPC

PTMs and X-ARAPUCAs

Warm cryostat

TPC Cold Electronics

Photon Detector System module
PTMs and X-ARAPUCAs

Wire plane during installation
Additional physics potentials from SBND-PRISM

- Further constrain neutrino interactions in oscillation physics.
- Perform targeted neutrino interaction measurements and disentangle nuclear effects.
- Background reduction moving off-axis.
SBN Sterile Neutrino Sensitivity

$\nu_\mu \rightarrow \nu_e$ Appearance sensitivity

$\nu_\mu \rightarrow \nu_x$ Disappearance sensitivity

SBN can cover the parameters allowed by past anomalies at 5$\sigma$ significance

SBN also has sensitivity to $\nu_\mu$ disappearance

The observation of $\nu_\mu$ disappearance would be essential to the interpretation of any electron neutrino excess as being due to the existence of sterile neutrinos


Additional studies including constraints from SBND-PRISM are ongoing.
4.7 $\sigma$ tension arises when combining $\nu_e$ appearance and $\nu_\mu$ disappearance data sets.

M. Dentler et al., JHEP 08:010 (2018)
Evolving Landscape...

Several alternative explanation of the MiniBooNE excess ($\nu_e$ appearance) but not $\nu_\mu$ disappearance have been proposed, together with other BSM scenarios at large.

### Dark Neutrinos
- Light $Z_D$ - Bertuzzo Jana Machado Zukanovich PRL 2018
- Bertuzzo Jana Machado Zukanovich PLB 2019
- Arguelles Hostert Tsai PRL 2019

### Transition Magnetic Moment
- Gninenko PRL 2009
- Coloma Machado Soler Shoemaker PRL 2017
- Atkinson et al 2021
- Vergani et al PRD 2021

### Axion-like particles
- Kelly Kumar Liu PRD 2021
- Brdar et al PRL 2021

### Heavy Neutral Leptons
- Long list, ex.
- Ballett Pascoli Ross-Lonergan JHEP 2017
- Kelly Machado PRD 2021

### Higgs Portal Scalars
- Pat Wilczek 2006
- Batell Berger Ismail PRD 2019

Note: not an exhaustive list!
Evolving Landscape...

Final state experimental signature: single photon, single electron, “trident” with di-leptons - overlapping and/or highly asymmetric, with different levels of hadronic activity

Dark Neutrinos

Transition Magnetic Moment

Axion-like particles

Heavy Neutral Leptons

Higgs Portal Scalars

Note: not an exhaustive list!
Evolving Landscape...

The unique capabilities of the LAr TPC technology open up more information than available in a Cherenkov detector (such as MiniBooNE)

• Characterize events in term of final state particle content and kinematics.
• Recognize the presence hadronic activity.

Collaboration between experimentalists and theorists is crucial for these searches!
Assuming HNL production predominately from $\tau^\pm$ decay: 
$D/D_s$ decay to $\tau$, that subsequently decay to HNLs

$\tau^\pm \rightarrow N X^\pm$ ($X^\pm$ is a SM particle e.g. $\pi^\pm$)

HNL decay (MC)

$N \rightarrow \nu \mu^+ \mu^-$

Searches for new physics in LAr TPC: ArgoNeuT

First search for Heavy Neutral Leptons $N \rightarrow \nu \mu^+ \mu^-$ in LAr TPC

0 events observed in the data

R. Acciarri et al., PRL 127 121801 (2021)

Significant increase in the parameter space exclusion region!
Searches for new physics in LAr TPC: ArgoNeuT

First search for Millicharged Particles in LAr TPC

mCP have an electric charge $Q = \epsilon \cdot e \ (\epsilon \ll 1)$

Low energy threshold (300 KeV) is the key!

Leading constraints in unexplored parameter region!
Signatures for new physics in LArTPC: SBND

Monte Carlo simulations

Dark Matter - electron-positron pair

Heavy Neutral Leptons - electron-positron pair

P. Ballet et al., JHEP 04 102 (2017)

Dark Neutrino - electron-positron pair

Machado et al., PRL 241801 (2018)

Dark Matter - forward electron

V. De Romeri et al., arXiv:1903.10505

SBND-PRISM: Signal is unfocused while background (ν-electron elastic scattering events) decrease with the off-axis angle

…several other studies and calculations of sensitivities ongoing

SBN(D) experiment(s) will explore the landscape and test not only the sterile neutrino hypothesis, but also other new physics models.
Signatures for new physics in LArTPC: SBND

Monte Carlo simulations

Dark Matter - electron-positron pair

\[ \chi_1 \rightarrow e^+e^- \]

J.R. Jordan et al., arXiv:1806.05185

Dark Neutrino - electron-positron pair

\[ N \rightarrow \mu^\pm \pi^\mp \]

Machado et al., PRL 241801 (2018)

Heavy Neutral Leptons - electron-positron pair

\[ \chi \rightarrow e^-e^+ \]

P. Ballet et al., JHEP 04 102 (2017)

MicroBooNE has searched for

- Heavy Neutral leptons
  
  \( N \rightarrow \mu^\pm \pi^\mp \) decay channel in a delayed time window

  P. Abratenko et al., PRD 101 052001 (2020)

- Higgs scalar portal (e^+e^- final state from NuMi off-axis events)

  P. Abratenko et al., PRL 127 151803 (2021)

Results recasted to constraint Heavy Neutral Leptons


Dark Matter - forward electron

\[ \gamma \rightarrow A' \]

\[ A' \rightarrow \chi (p_1) \]

\[ \chi \rightarrow \bar{\chi} (p_2) \]

V. De Romeri et al., arXiv:1903.10505

SBND-PRISM: Signal is unfocused while background (ν-electron elastic scattering events) decrease with the off-axis angle

[Graphs and plots showing event simulations and analysis results]
The SBN science program includes precision studies of neutrino-argon cross sections.

- MicroBooNE has provided several neutrino-argon cross section measurements.*
- ICARUS-T600 collects 100k neutrino events per year from NuMI off-axis.
- SBND will make the world’s highest statistics cross section measurements by recording 2 million neutrino interactions per year from BNB.

A generational advance in neutrino-nucleus interaction studies!

*See D. Caratelli at this conference (on Tuesday), for a review of MicroBooNE cross section measurements.
Precision Studies of Neutrino-argon Interactions in SBND

With its proximity to the neutrino source, SBND will compile neutrino data with unprecedented high event rate and provide precision studies of neutrino-argon interactions in the sub-GeV and GeV energy range.

$\sim 5000 \nu$ events/per day!

In three months SBND will collect as much data as MicroBooNE has collected in five years.

1.5 million $\nu_\mu$ Charged Current (CC) and 12,000 $\nu_e$ CC interactions per year.

Inclusive and exclusive measurements of different final states for $\nu_\mu$ and $\nu_e$, measure nuclear effects and rare processes

SBND-PRISM: perform targeted neutrino interaction measurements.
Summary

LAr TPC neutrino detectors at Short-Baseline are fantastic tools to look for new physics in the neutrino sector and beyond!

ArgoNeuT, a small LAr-TPC provided first neutrino cross sections and leading constraints on millicharged particles and heavy neutral leptons in unexplored parameter space regions.

MicroBooNE completed the first search for low energy excess, other BSM searches and several neutrino-argon cross section measurements.

The SBN detectors will perform a world-leading search for eV-scale sterile neutrinos.

Beyond oscillation searches, the SBN program has a broad science goal, which addresses alternative explanations of the SBL anomalies, includes other BSM explorations and precision studies of neutrino-argon interactions.
OVERFLOW
Experimental Hints For Beyond Three Neutrino Mixing

Sterile Neutrinos?

Low energy $\nu_e$ beam from a decay-at-rest pion beam (Los Alamos, 1993-1998)

LSND
Baseline 30 m
E= [20 – 50] MeV
L/E ≈ 1 m/MeV

MiniBooNE
Baseline 540 m
E=[0 - 2] GeV
L/E ≈ 1 m/MeV

167 tons liquid scintillator

Decay in flight neutrino source (Booster Neutrino Beam - Fermilab)

800 tons mineral oil

Oscillation signal?

Low-energy excess

+ Reactor and Gallium “anomalies”
LArTPC at work

Charged particles in LAr produce free ionization electrons and scintillation light.

Ionization charge drifts in a uniform electric field towards the readout wire-planes.

Digitized signals from the wires are collected [time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge].

$m.i.p. \text{ at } 500 \text{ V/cm}: \sim 60,000 \text{ e/cm} \\
\sim 50,000 \text{ photons/cm}

Electron drift time ~ ms

VUV photons propagate and are shifted into VIS photons

Scintillation light fast signals from LDSs give event timing