The MicroBooNE Detector

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David Caratelli @ Fermilab
On behalf of the MicroBooNE Collaboration
Why build the MicroBooNE Detector?

**Oscillation physics goals:** Precision PMNS mixing matrix: mass ordering, $\delta_{CP}$, sterile neutrino searches.

Achieving this program requires a new level of **precision** for accelerator-based neutrino measurements.

Neutrino **energy** determination is essential for these measurements.

MicroBooNE investigates sterile neutrinos @ Fermilab. **Detector needs** are the same for other SBN and DUNE programs.
What we want from our detector

We want to use our detector to accurately measure neutrino energies & flavor. Detailed information from neutrino interaction is essential due to complex nature of interaction at 1 GeV.

Need a detector capable of performing accurate particle identification with low thresholds.
LArTPC allows to extract full details of $\nu$ interaction.

This gives us:

1) more accurate energy reconstruction.
2) background rejection in $\nu_e$ oscillation measurement.

MicroBooNE is leading the way in the development of techniques employed for the reconstruction, calibration, and analysis of large-scale LArTPC neutrino experiments.
MicroBooNE in a nutshell

**Liquid Argon Time Projection Chamber.** Measures ionization electrons and scintillation light produced by traversing charged particles.

JINST 12, P02017 (2017)

By the **numbers**:

10 x 2.5 x 2.3 meters → 87 tons of LAr.
Surface detector → 5 kHz cosmic-ray rate.
8k wires → mm spatial resolution.
70 kV → 2.3 ms drift-time.
32 PMTs for timing / background rejection.
Cosmic Ray Tagger installed in 2016/17
MicroBooNE Studies Neutrino Interactions on the Booster Neutrino Beamline at Fermilab.

1 GeV $\nu_\mu \rightarrow 1$ neutrino interaction per minute.

Data taking started in Fall 2015.

Three years of stable operations.

9.5 x $10^{20}$ POT of $\nu$ beam $\rightarrow 10^5$ interactions.

> 95% DAQ uptime.

MicroBooNE is the largest LArTPC currently operating worldwide.

Strong team of physicists, engineers and technicians maintaining many subsystems.

Strive to share knowledge with LArTPC community

- e.g. cryo, HV, electronics.
How to go from high-resolution images to quantitative measurements

1) Pattern Recognition
Signal formation and signal processing

Extensive development of advanced techniques for noise-filtering and signal-processing.

*Noise filtering*: JINST 12 P08003 (2017)


Total absorption calorimeter with **anisotropic** response.

Different wire-planes and wire orientation causes significant variation in detector response.
High level pattern recognition

Multi-staged approach to perform high-quality pattern recognition.

1) event-slicing to isolate individual interactions

2) low-level pattern recognition

3) full interaction reconstruction

Pandora multi-algorithm pattern-recognition

High level pattern recognition

Broad R&D program developing advanced techniques for pattern-recognition employing numerous methods.

Development of pixel-based particle ID via convolutional neural networks

New developments and ideas!
How to go from high-resolution images to quantitative measurements

2) Particle kinematics for physics analyses
Two-step calibration of energy response:

1) Produce uniform response map.
   - accounts for quenching & electric field distortions.

2) Calibrate absolute energy scale with stopping muons.

Allows for:

- Calorimetric energy reconstruction
- Particle identification
millimeter position and vertexing resolution translates into:

- accurate momentum determination (few %).
- high resolution for vertex activity.

Good position resolution enables better measurement of kinematics.

Studies from MICROBOONE-NOTE-1049-PUB
Multiple Coulomb Scattering energy estimation achieves **10% resolution** in MicroBooNE.

Refined MCS technique specific for argon.

Employed for $P_\mu$ determination in many analyses. Data-driven evaluation of technique.


Updates on data-driven studies in MICROBOONE-NOTE-1049-PUB
Calibrating Electromagnetic Interactions

300 MeV e- showers in LAr

- Radiative $\gamma$
- Isolated energy deposition
- Track-like energy deposition
Electron and photon reconstruction is key to oscillation measurements.

MicroBooNE has developed the first fully-automated reconstruction tools for EM reconstruction in LArTPCs.

Focus on studying energy reconstruction performance. 20% resolution, with good data-MC agreement.

Michel electrons and photons from $\pi^0$ are used for these studies.
The MicroBooNE experiment has been taking data on the Booster Neutrino Beamline since Fall of 2015.

→ Largest sample of low-energy neutrino interactions on Ar.

Leading the development and building expertise necessary to take full advantage of LArTPC technology for O(1) GeV neutrino oscillation measurements.

→ Fully transferable to DUNE and SBN.

Presented latest results on detector performance, from calibrations to reconstruction.

These results directly impact the physics we extract from our detector.

→ see “Latest Results from MicroBooNE” by Pip Hamilton for Analysis Status

MicroBooNE public notes accessible @ http://microboone.fnal.gov/public-notes/
Backup
LArTPC Working Principle

- Drift coordinate: 2.56 m
- Beam coordinate: 10.32 m
- Vertical coord.: 2.32 cm

Charged particles ionize argon

Neutrino interacts with Ar
LArTPC Working Principle

isotropic UV scintillation light.
LArTPC Working Principle

Electronics in cold: High signal-to-noise enables accurate calorimetry.
BNB and NuMI Beamlines

Booster 8 GeV

BNB 8 GeV

NuMI 120 GeV

Beryllium target

HORN: 174 kA

~700 MeV ν energy.

~0.1% νₑ contamination.

Diagram showing the interaction of particles (μ⁺, μ⁻, K⁺, K⁻) and the decay of K⁻ to μ⁻ and π⁻, with ν and ν̄ interactions.
MicroBooNE’s neutrinos

MicroBooNE studies neutrino interactions on the Booster Neutrino Beamline at Fermilab.

O(1 GeV) $\nu_\mu$ beam. 400 meter baseline $\rightarrow$ L/E $\sim$ 1 eV$^2$.
Electron Attenuation by Impurities

Drifting electrons are absorbed by impurities in the argon.

H2O and O2 are the main sources of e- attenuation.

This causes a drift-distance dependent signal attenuation which must be calibrated out.

MicroBooNE design: obtain a 3 ms lifetime. Currently well above 10 ms.

Electron lifetime is so high that drift-dependent variation in charge response is sub-dominant to effect caused by distortions in the electric field (see next slide).

Both generally contained to the 5% level.
MicroBooNE LAr quality:

- Air evacuation during commissioning (fill cryostat volume with heavy Ar from bottom → remove impurities in air).
- Recirculation and impurity filtration allow to clean Ar as impurities build up.
- Well beyond our design goal of 3 ms argon lifetime.
Electronics Noise

Temperature Dependence of Noise in TPC

Error bars represent the standard deviation of RMS noise over all collection plane wires.

660 ENC goal from TDR

Noise levels in MicroBooNE:
MICROBOONE-NOTE-1001-TECH
Interactions in Argon
Electron / Photon Separation

**Figure 1:**
- **Left panel:** NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.
- **Right panel:** BNB DATA: RUN 5235 EVENT 1915. MARCH 2, 2016.

**Graph:**
- Simulated Electron Candidates
- Simulated Gammas
- Electrons, Data
- Photons, Data

**Statistical Significance:**
- Area Normalized

**Reference:**
Positive ions drift 105 times slower than e- in Lar.

Buildup of Ar+ in TPC in steady-state configuration.

The Ar+ ions distort the electric field causing:

1) variations in drift direction → spatial distortions

2) variations in E-field strength → calorimetry distortions.

Space-charge simulation matches qualitatively effects seen in data.

Work ongoing to produce a calibration map of field distortions caused by the Space Charge Effect through laser and cosmic-ray muon measurements.
Calorimetric Energy Reconstruction

Physics of energy loss in LAr:

Argon is ionized by traversing charged particles.

Positive ions recombine with $e^{-} \rightarrow$ signal loss.

Impurities capture drifting $e^{-}$s $\rightarrow$ signal loss.

All need to be accounted for in order to recover MeV scale given the collected electrons on the sense-wires.
Ion Recombination

Recombination depends on density of $\text{Ar}^+$ and $\text{e}^-$. Affected by:

- $dE/dx$ (more energy deposition per unit distance → larger ion density → more recombination)
- E-field strength: determined timescale at which $\text{Ar}^+$ / $\text{e}^-$ drift away from each other.

For electrons / photons much smaller variation in $dE/dx$ vs. energy compared to muons/protons/pions. → significant effect, but $\sim$constant.
Michel Electrons

Abundant sample of Michel electrons from decay-at-rest cosmic-ray muons.

Valuable sample to study EM interactions near the critical energy.

Complex topology: similar contributions from ionization / radiative losses.

JINST 12 P09014 (2017)

Good data-MC agreement.

Spectral distortion due to lossy impact of calorimetric energy reconstruction.

Recovering radiative photons improves energy reconstruction:

30% → 20%
\( \pi^0 \rightarrow \gamma \gamma \) EM Showers

Tens to hundreds of MeV energy range photon showers.

\( \pi^0 \) mass valuable calibration “line”.

Simulation-based energy corrections account for lossy effect of clustering and thresholding.

Recover correct mass, with good agreement between data/MC.
Calibrating Electromagnetic Interactions
3D Coverage

Active detector if require three live wire planes in tiling

Active detector if require two live wire planes in tiling

MicroBooNE Preliminary

MICROBOONE-NOTE-1040-PUB
Multiple Coulomb Scattering energy estimation achieves 10% resolution in MicroBooNE. Employed for $P_\mu$ determination in many analyses. Data-driven evaluation of technique.