MicroBooNE:
Recent Results and a Focus on the Future

Lauren Yates (Fermilab) on behalf of the MicroBooNE Collaboration
55th Annual Fermilab Users Meeting
June 16, 2022
MicroBooNE Experiment at a Glance

- MicroBooNE observes neutrino interactions using a LArTPC
  - BNB: on-axis, flux peaks at ~600 MeV
  - NuMI: off-axis by ~8°, flux peaks low but goes out to a few GeV
- Completed five years of beam physics data-taking, collected largest neutrino–argon interaction dataset
- Also completed several post-operations R&D studies
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Thank you to Fermilab for excellent support of neutrino beams, operations, and data processing!
MicroBooNE Detector: A Liquid Argon Time Projection Chamber

- LArTPCs are highly-capable, fully-active tracking calorimeters
- Detailed images of interactions with ~3 mm spatial resolution enable low thresholds and excellent particle identification
MicroBooNE’s Scientific and Technical Accomplishments

Searching for New Physics

- Understanding $\nu$–Ar Interactions
- Performing key tests of models
- Measuring a variety of inclusive and exclusive cross-sections
- Leveraging powerful detector, largest $\nu$–Ar interaction dataset

Understanding $\nu$–Ar Interactions

- Advances in detector physics, modeling, signal processing, and calibration
- Developed multiple novel reconstruction techniques
- Post-operation R&D studies

Understanding LArTPCs & Developing Techniques

- Searching for several other BSM physics signatures
- Addressing origin of LEE anomaly
- Investigating sterile neutrinos via short baseline oscillations

More than 45 publications written by MicroBooNE in the past 5 years
More than 75 public notes sharing progress with community as we go

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Understanding LArTPCs & Developing Techniques

- MicroBooNE has contributed to significant advances in LArTPC detector physics, modeling, and reconstruction
- Post-operations R&D studies are just beginning to bear fruit

Electron Diffusion Measurement
JINST 16, P09025 (2021)

Novel Sim. Modification
EPJ C 82, 454 (2022)

Wire-Cell Reconstruction Tools
JINST 16, P06043 (2021) + more

Deep Learning Tools
PRD 103, 052012 (2021) + more

Radon Mitigation R&D Study
arXiv:2203.10147

166.5 cm
3 μrem/h
3 μrem/h
8 μrem/h
12 μrem/h
12 μrem/h
12 μrem/h
12 μrem/h
3 μrem/h
3 μrem/h
1 μrem/h
1 μrem/h

Atrazhev-Timoshkin
Li et al. Parametrization
Li et al. Data
ICARUS
MicroBooNE Data

MicroBooNE Simulation

Original Waveform
Modified Waveform
Original Hits

Original Waveform
Modified Waveform
Original Hits

MicroBooNE Data

MicroBooNE
Subrun 72
Event 3633
Eng=1060 MeV
T-plane

MicroBooNE Data
Understanding Neutrino–Argon Interactions

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Neutrino Interactions

- Discovery science with neutrinos requires understanding and modeling interactions
  - Essential for interpreting final state particle content and kinematics to extract neutrino properties
- Theory is complex due to multiple channels, nuclear effects, final-state interactions
- Cross-section measurements are key to benchmarking models and improving them
$\nu_\mu$ CC Inclusive: Probing Hadronic Energy

- Recent MicroBooNE $\nu_\mu$ charged-current inclusive measurement focuses on hadronic energy
  - Critical for estimating the neutrino energy, which in turn is necessary for neutrino oscillation measurements
- Probes the physics of the final-state hadronic system
- Model validated using novel constraint procedure
- More on this at the JETP Seminar tomorrow!
- And more to come: higher statistics, multi-differential

MICROBOONE-NOTE-1110-PUB
$\nu_\mu$ CC Exclusive Measurements: Probing Nuclear Physics

- Additionally, exclusive measurements of $\nu_\mu$ charged-current interactions on argon probe specific aspects of nuclear physics modeling with unprecedented detail.
- Targeting $1_\mu 1p0\pi$ topology and using transverse kinematic imbalance (TKI) variables to investigate nuclear effects in argon — initial nucleon motion, final state interactions.
- Targeting $1_\mu 2p0\pi$ topology to study meson exchange currents (MEC).
$\pi^0$ Final States: Probing Pion Production

- Recently published a measurement of NC $1\pi^0$ cross section on argon
- Also first exclusive measurements of NC $1\pi^0$ cross sections on argon
- Measure a smaller cross section than predicted by all of the models studied
  - Result is $\sim 1\sigma$ (sys+stat) from GENIE v3

- More to come:
  - Differential $\nu_\mu$ CC $1\pi^0$ measurement
    MICROBOONE-NOTE-1107-PUB
  - Differential NC $\geq 1\pi^0$ measurement
    MICROBOONE-NOTE-1111-PUB
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The MiniBooNE LEE Anomaly

- MiniBooNE studied $\nu_\mu \rightarrow \nu_e$ appearance using the BNB beam and a mineral oil Cherenkov detector
- MiniBooNE’s final results show a $4.8\sigma$ excess of $\nu_e$-like events, called the low-energy excess (LEE)

- MicroBooNE’s first searches addressing the LEE anomaly pursue two main hypotheses:
  - Electrons from charged-current $\nu_e$ interactions (greens)
  - Single photons from neutral-current Delta resonance radiative decays, NC $\Delta \rightarrow N\gamma$ (yellow)
MicroBooNE’s First LEE Results: Electrons

- Three MicroBooNE analyses searched for an enhanced rate of low-energy $\nu_e$ interactions
  
  - $1e1p$ CCQE: events with $1e1p$ topology and kinematics consistent with two-body scattering
    PRD 105, 112003 (2022)
  
  - $1eNp + 1e0p$: events with no pions in the final state
    PRD 105, 112004 (2022)
  
  - $1eX$: events with any hadronic final state
    PRD 105, 112005 (2022)
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    PRD 105, 112005 (2022)
- Observations in low-energy region consistent with intrinsic $\nu_e$ rate expected from the BNB
  - No evidence for an excess of low-energy $\nu_e$
MicroBooNE’s First LEE Results: Single Photons

- MicroBooNE’s single photon search studied two topologies: $1\gamma 1p$ and $1\gamma 0p$
- Main background to this search is NC $\pi^0$ events, which were constrained by side-band samples identified using parallel analysis tools
- No excess consistent with an enhancement of NC $\Delta \rightarrow N\gamma$ is observed, and sets a limit on the effective branching ratio for this decay that is 50× better than previous

PRL 128, 111801 (2022)
Searches for Sterile Neutrinos

- Building on first LEE results, now pursuing searches for sterile neutrinos within the 3+1 oscillation framework
- A $1\mu1p$ CCQE selection used in the $1e1p$ analysis has been used to study $\nu_\mu$ disappearance in the BNB
- Selections used in the fully inclusive $1eX$ analysis have been used to study general 3+1 oscillations in BNB
- Results so far consistent with three neutrinos
- More coming soon:
  - Joint $1e1p+1\mu1p$ analysis in the BNB MICROBOONE-NOTE-1105-PUB
  - Inclusive analysis combining BNB and NuMI MICROBOONE-NOTE-1116-PUB
  - Future analyses addressing other sterile models

Data 90% CL 3+1 Disappearance

![Graph showing data 90% CL 3+1 Disappearance](image)
Investigating Other LEE Models

- Theory landscape related to the LEE anomaly continues to evolve — many new models involving photons or $e^+e^-$ pairs in the final state
- Currently expanding investigations of photon-like and $e^+e^-$ pair channels
  - Some preliminary results are shown below, and even more is on the way
- MicroBooNE will continue to test many LEE-motivated models of new physics, leveraging the excellent performance of our LArTPC detector and multiple reconstruction paradigms
Searching for Other New Physics Signatures

- MicroBooNE is also capable of searching for many other new physics signatures
- Searched heavy neutral leptons from BNB decaying to $\mu\pi$ pairs
  
- Searched for Higgs portal scalar bosons from NuMI decaying to $e^+e^-$ pairs
- Searching for neutron-antineutron oscillations from neutrons bound in detector’s argon nuclei
- More coming soon:
  - Updated heavy neutral lepton search
  - Updated Higgs portal scalar boson search
  - Search for dark trident interactions
  - Search for millicharged particles
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A Focus on the Future

- The full Short Baseline Neutrino (SBN) program, which includes ICARUS and SBND, has much more exciting physics yet to come
- SBN is critical to building LArTPC expertise leading up to the DUNE long-baseline oscillation experiment
- Will hear more about SBND, ICARUS, and DUNE in the next few talks!
Thank you!