MiniBooNE observed an excess of EM activity at low energies in the Booster Neutrino Beam at Fermilab.

→ “low energy excess” or LEE.

Part of a broad range of Short Baseline Anomalies.

Electron or photon? New physics?
**Why MicroBooNE?**

**MicroBooNE** was built to determine the nature of this excess.

Rely on the LArTPC detector technology to disambiguate electron vs. photon signals.
The Road to MicroBooNE physics

The road to MicroBooNE’s low-energy-excess analysis...

- stable operations for large-scale LArTPC detector
- Development of electron / photon analyses sensitive to new physics.
- sideband validation
- final box-opening
- MicroBooNE cryostat being transported to detector hall @ Fermilab in Summer 2014

Many milestones along the way. MicroBooNE has pioneered the development of the LArTPC detector technology towards enabling precision neutrino physics.
Testing the $e^-$ and $\gamma$ LEE hypotheses

Extensive literature rich in ideas to explain the origin of the MiniBooNE low-energy-excess.

The first generation of MicroBooNE analyses target two specific hypotheses:

Both start with the MiniBooNE excess \cite{PRL 121, 221801 (2018)} unfolded into a true electron-like or photon-like signal which is propagated through the MicroBooNE flux simulation.

Analyses’ sensitivity benchmarked against these hypotheses.

**electron** signal model:
scaling of intrinsic $\nu_e$ from the beam

**photon** signal model:
scaling of NC $\Delta$ radiative decay to single $\gamma$.

MiniBooNE signal unfolding to MicroBooNE: MICROBOONE-NOTE-1043
Multiple analyses utilizing different tools and approaches.

Will highlight common aspects to the various analyses, and briefly introduce each analysis’ key features.

Many more details in the Public Notes describing each of the analyses. Can reach out with questions at microboone_info@fnal.gov

\underline{γ channel:}

"The MicroBooNE Single-Photon Low-Energy Excess Search"
[MICROBOONE-NOTE-1087]

\underline{e^- channel:}

“Event Selection in the MicroBooNE Deep Learning Based Low Energy Excess Analysis Using Two-Body Scattering Criteria”
[MICROBOONE-NOTE-1086]

“Search for Electron Neutrinos in Multiple Topologies with the MicroBooNE Experiment”
[MICROBOONE-NOTE-1085]

“Status of Electron Neutrino Event Selection at1MicroBooNE Using the WireCell-Pandora Hybrid Reconstruction Approach”
[MICROBOONE-NOTE-1088]
Identifying Neutrinos in MicroBooNE

Surface LArTPC + slow e- drift → large cosmic background.

All LEE analyses start with the need to isolate neutrinos in a sea of cosmic-rays.

“off-beam” data used for data-driven assessment of cosmic backgrounds.

start with: $4 \times 10^8$ off-beam triggers x O(10) cosmics/event
end with: < 1 background events in final distributions.
Detector Modeling

Leverage a strong program of low-level detector modeling:


→ good understanding of detector response and precise measurement of particle kinematics.

Proton and muon data dE/dx vs. residual range and theoretical expectation.

MicroBooNE Preliminary 5.89e+20 POT
- $\nu_e$ CC: 0.8
- $\nu_e$ CC: 3.9
- $\nu_e$ CC: 10.2
- Out. fl. vol.: 4.10
- $\nu$ CC: 47.5
- Cosmic 107.2
- BNB: 2452

$M_{YY}$ – area normalized

Data NC $\pi^0$ candidate

Data $dE/dx$ vs. residual range and theoretical expectation.
Accurate modeling of $\nu$-Ar interactions is paramount to this analysis.

Sparse $\nu$-Ar measurements and few constraints at low energies require in-situ measurements.

See talk by Raquel Castillo Fernandez.

Three generations of MicroBooNE analyses with progressive improvements on simulation, reconstruction, analysis tools.

State-of-the-art neutrino interaction model with GENIE-v3 + data-driven model tune with T2K CC0\pi data

- Detector systematics $O(10\%) \rightarrow O(\text{few \%})$
- Reconstruction tools capable of $4\pi$ measurements.
- Robust $\nu$ interaction modeling and good data/MC agreement.
Constraining Backgrounds to LEE analyses

Background uncertainties drive sensitivity to new physics.

Leverage flux & cross-section correlations between $\nu_e$ and $\nu_\mu$.

NC $\pi^0$ measurement constraints single-$\gamma$ background.

CC $\nu_\mu$ constrains intrinsic $\nu_e$s.
MicroBooNE’s low-energy-excess analyses
The single-photon LEE search

Select final-state compatible with a single photon shower and one or zero protons.

BDT tailored to NC $\Delta \rightarrow \gamma + N$ signature.

- Most stringent constraint of standard model NC $\Delta \rightarrow \gamma + N$ in neutrino scattering.
- Capable of excluding radiative $\Delta$ decay interpretation of LEE hypothesis at > 95% CL

See talk by Mark Ross-Lonergan.

Leverage Pandora reconstruction

[EUR.PHYS.J.C 78 (2018) 1, 82]
The electron channel LEE search

Three distinct efforts within the collaboration:

**MICROBOONE-NOTE-1085**
multi-topology search over broad energy range.
Leverage LArTPC PID.

**MICROBOONE-NOTE-1086**
Tailored search for low-energy CCQE-like $\nu_e$.
Deep-Learning techniques.

**MICROBOONE-NOTE-1088**
Aim for inclusive $\nu_e$ search.
ongoing development.

WireCell tomographic imaging
The electron channel LEE search


Tailored search for low-energy CCQE-like $\nu_e$.

Deep-Learning techniques.

Over-constrain interaction kinematics under two-body scattering CCQE-like hypothesis

$$E_{\nu_{CCQE}}^y (E_{\text{proton}}, \theta_{\text{proton}}) = E_{\nu_{CCQE}}^y (E_{\text{lepton}}, \theta_{\text{lepton}}) = E_{\text{range}} (E_{\text{proton}}, E_{\text{lepton}})$$
The electron channel LEE search

“Search for Electron Neutrinos in Multiple Topologies with the MicroBooNE Experiment”
[MICROBOONE-NOTE-1085]

MICROBOONE-NOTE-1085
multi-topology search over broad energy range.

Leverage LArTPC PID.

→ 3σ sensitivity to exclude SM in favor of $\nu_e$ LEE interpretation
The **electron** channel LEE search

“Status of Electron Neutrino Event Selection at MicroBooNE Using the WireCell-Pandora Hybrid Reconstruction Approach” [MICROBOONE-NOTE-1088]

WireCell tomographic imaging

**Before Wire-Cell cosmic rejection**

**After Wire-Cell cosmic rejection**

Aim to leverage strengths of different reconstruction paradigms for high efficiency $\nu_e$ measurement.

At earlier stages of development.

First event selections from Wire-Cell “hybrid” analysis.

MICROBOONE-NOTE-1088

Aim for inclusive $\nu_e$ search.

ongoing development.
MicroBooNE’s “Low Energy Excess” analyses:
- being validated with 5% open-data and through $\nu_e / \pi^0$ sidebands far from signal region
- nearing a full box-opening.

Promising results indicating robust analyses.
MicroBooNE aims to address the origin of MiniBooNE’s low-energy-excess anomaly, shedding light on a significant anomaly in short baseline neutrino experiments.

Leveraging multiple years of development in analyzing ν-LArTPC data MicroBooNE has multiple complementary analyses sensitive to new physics at low-energy.

Mature analyses have been validating performance with sidebands.

First generation of analyses getting ready for final box-opening.

→ stay tuned!