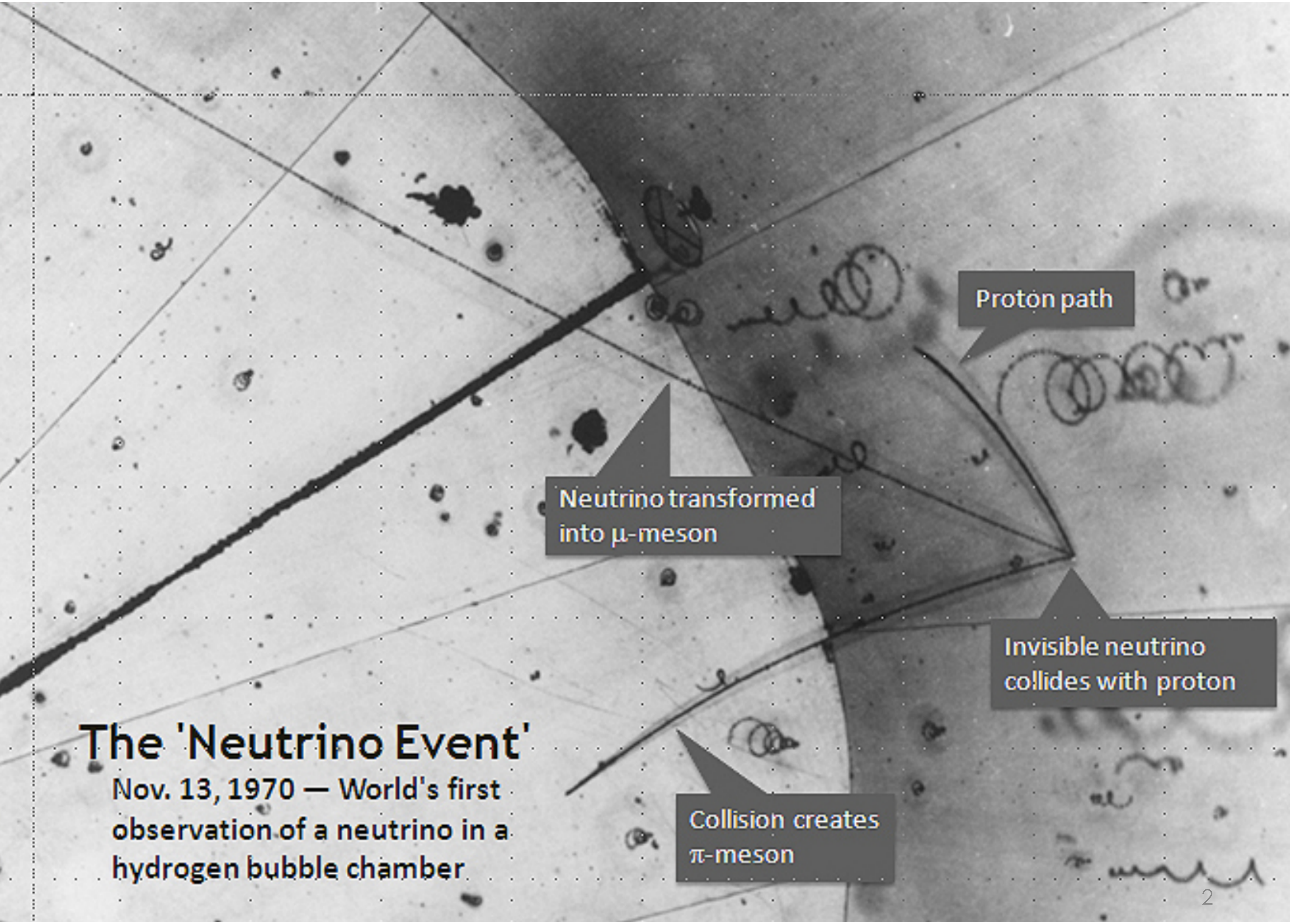
Neutrino Physics with MicroBooNE

Georgia Karagiorgi, on behalf of the MicroBooNE Collaboration

Nevis Laboratories
Columbia University

39th International School of Nuclear Physics
Neutrinos in Cosmology, in Astro-, Particle and Nuclear Physics
Erice, Sicily
Sep. 16-24, 2017

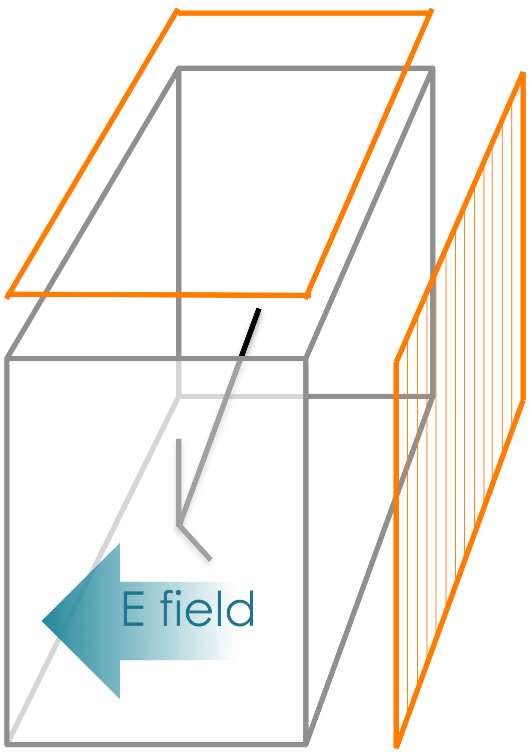


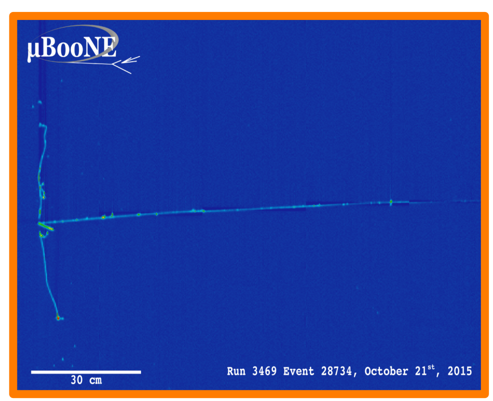
The 'Neutrino Event'

Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber

… 45 years later …

LArTPC operating principle:
A high-resolution 3D camera for ionizing particles





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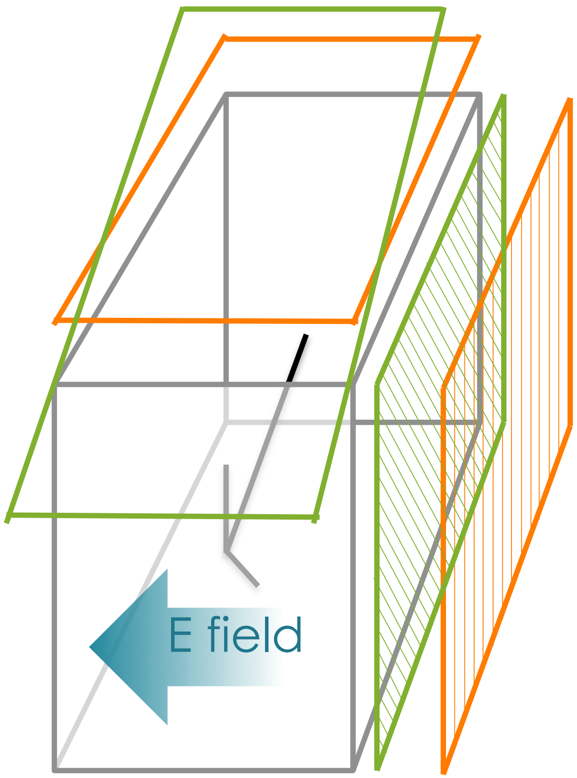

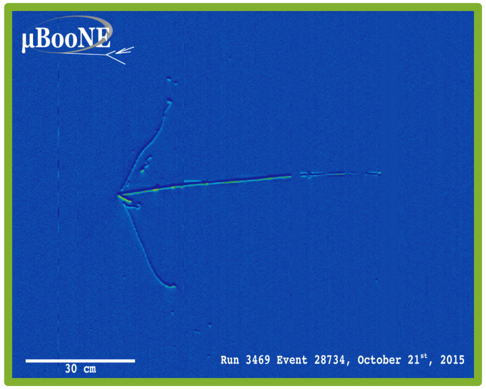

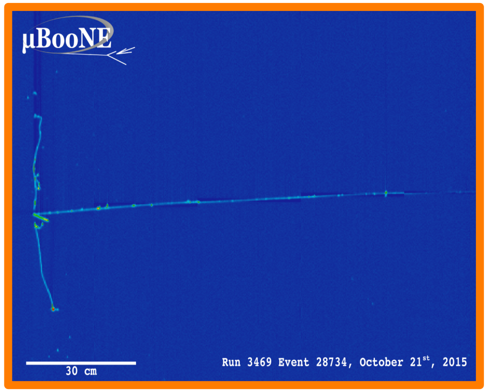

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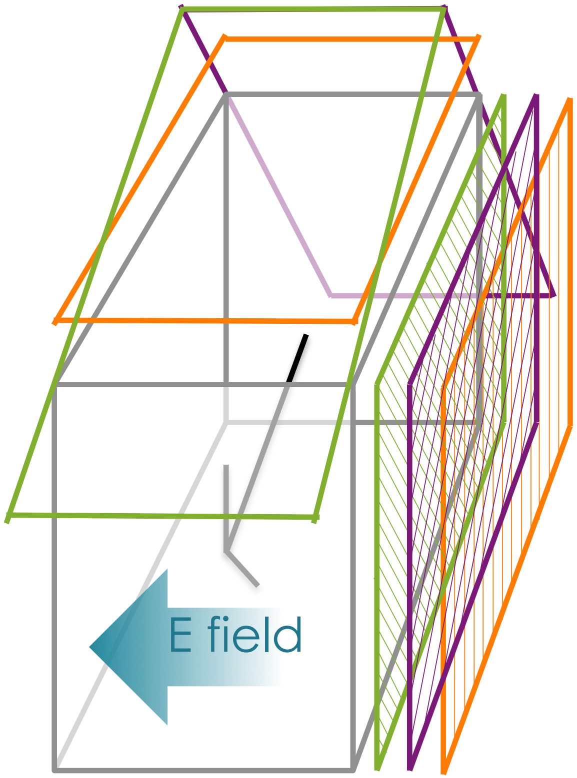

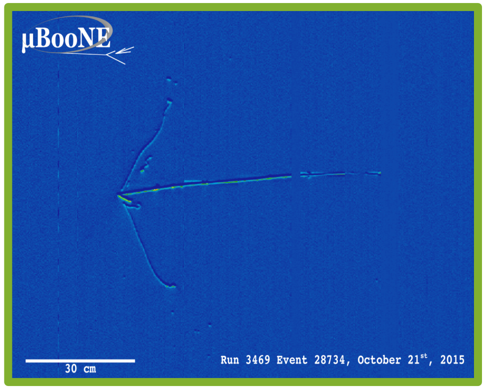

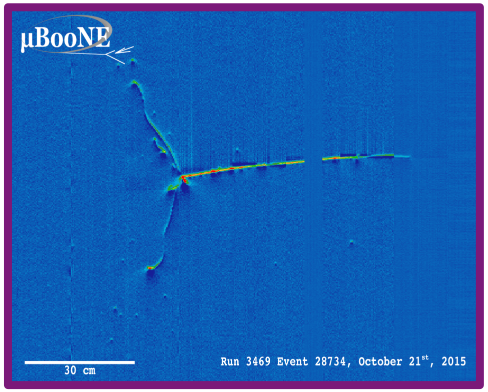

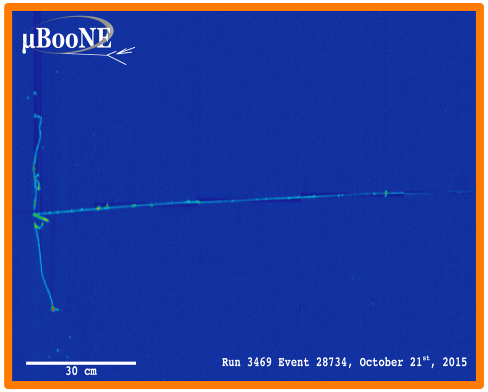

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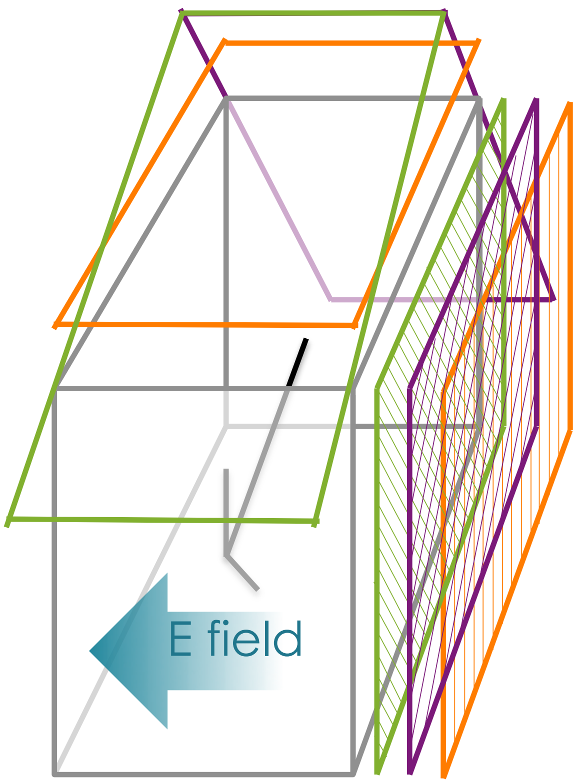
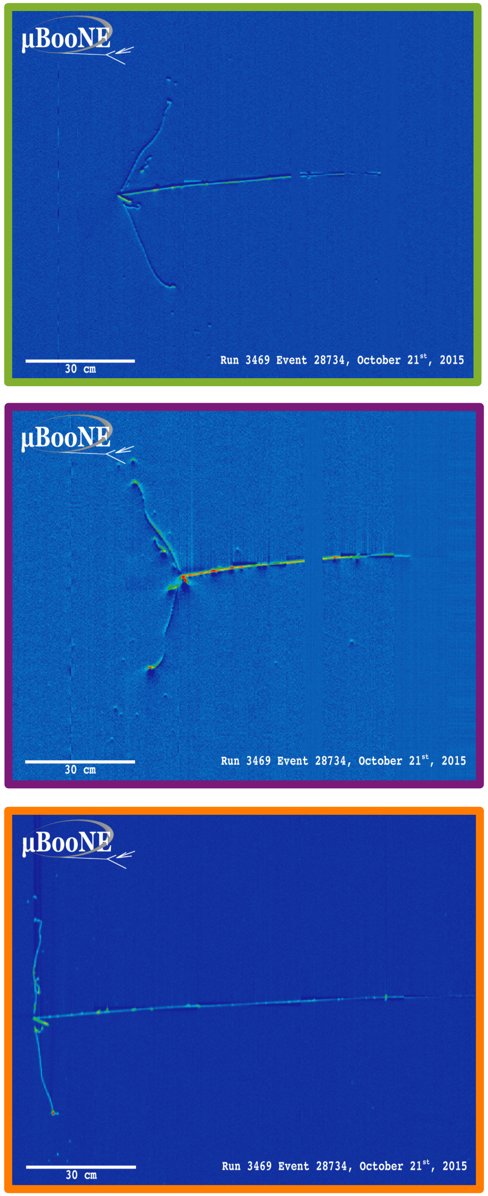
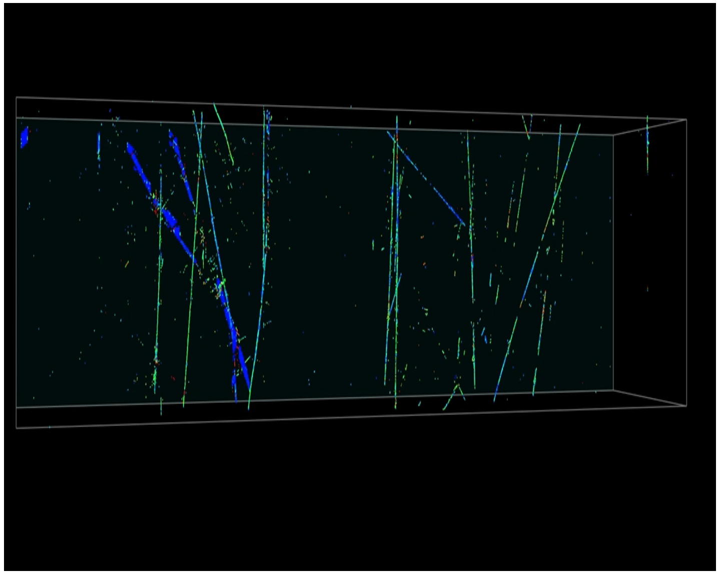




625 pictures per plane per second
~2700 x 3200 = 8.6M pixels each

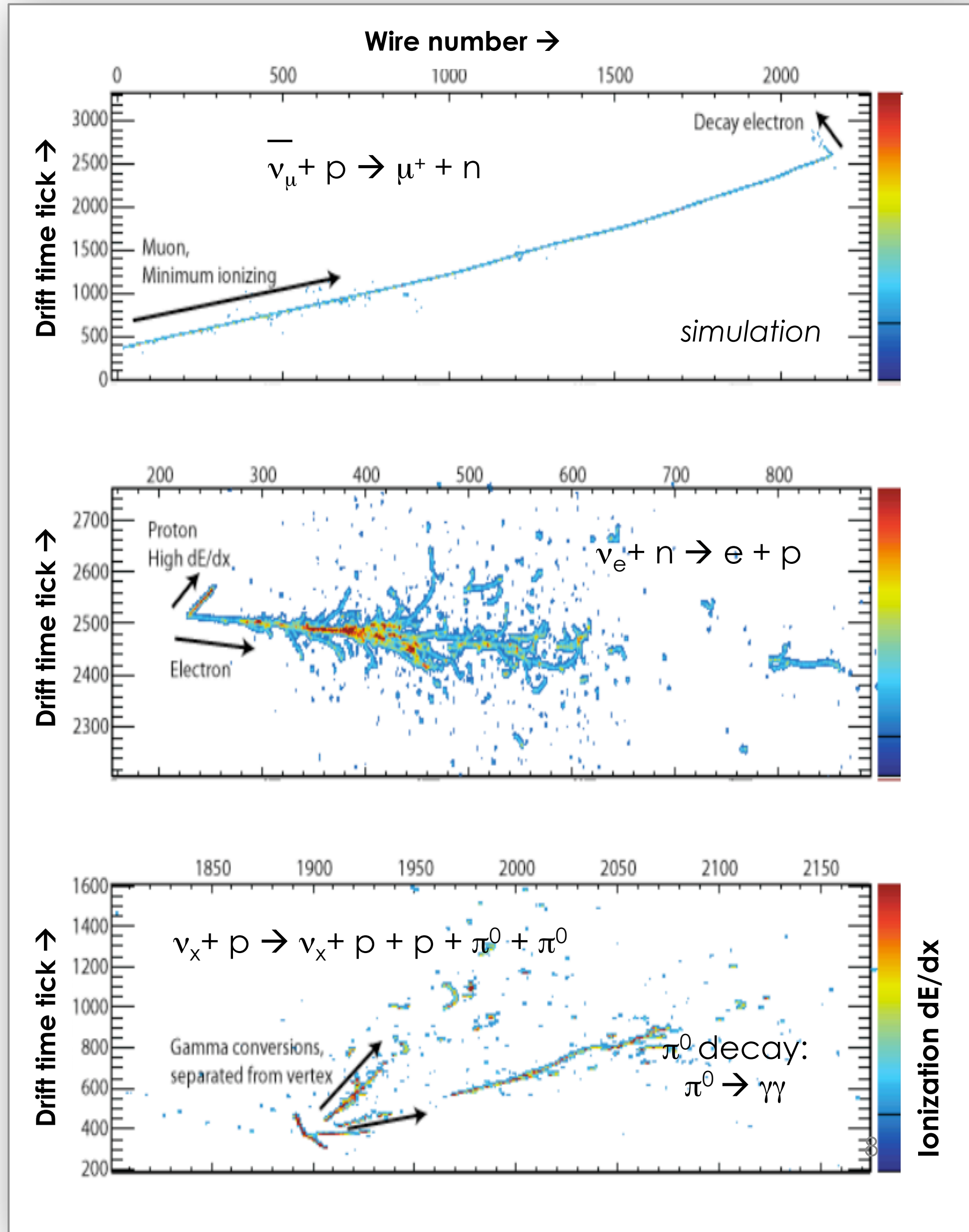
(each 3mm x ~0.8mm)



Can resolve minimum-ionizing particles (MIPs) to few overlapping protons based on local ionization energy deposition

LArTPC detectors in ν physics

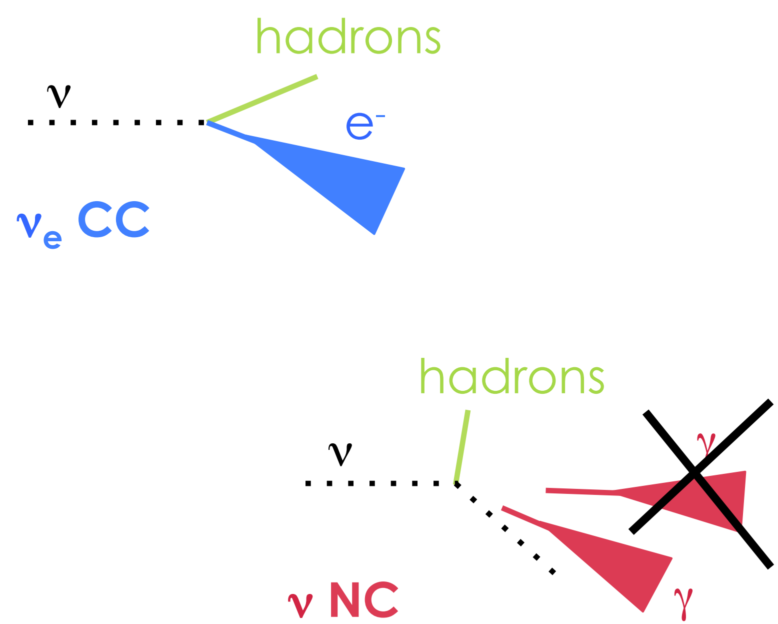
- **Large, continuous, fully active volume** acts as both target and detector medium
- **High density**
  → high interaction probability
  → higher statistics for same exposure
- **High ionization and scintillation yield** and high transparency
  → low detection thresholds, higher detection efficiency
- **High digitization rates, segmentation**
  → high position and dE/dx resolution
  → better particle identification
- **Relatively inexpensive**
  → scalable to larger and larger sizes

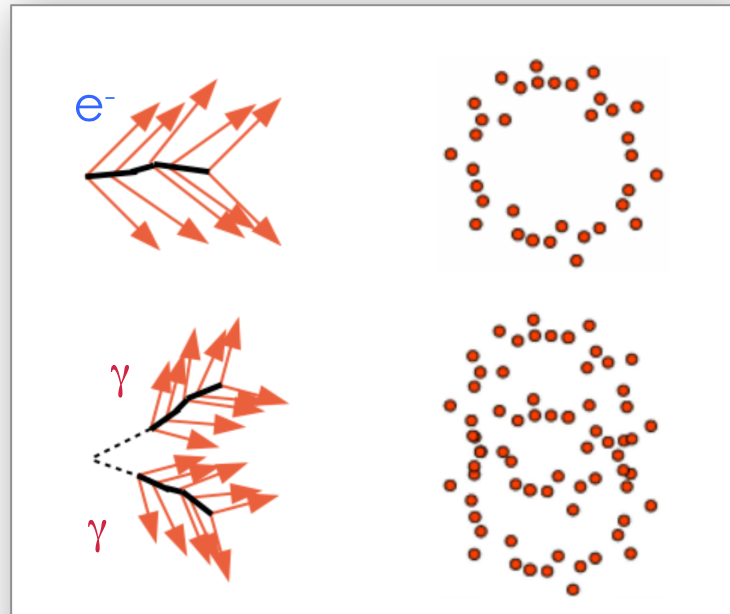


Electron/Photon Separation

A **single e** and a **single γ** are indistinguishable in traditional, Cherenkov detectors; ν_e measurements are plagued by NC $\pi^0 \rightarrow \gamma\gamma$ or other single-photon backgrounds…

but not in a LArTPC!



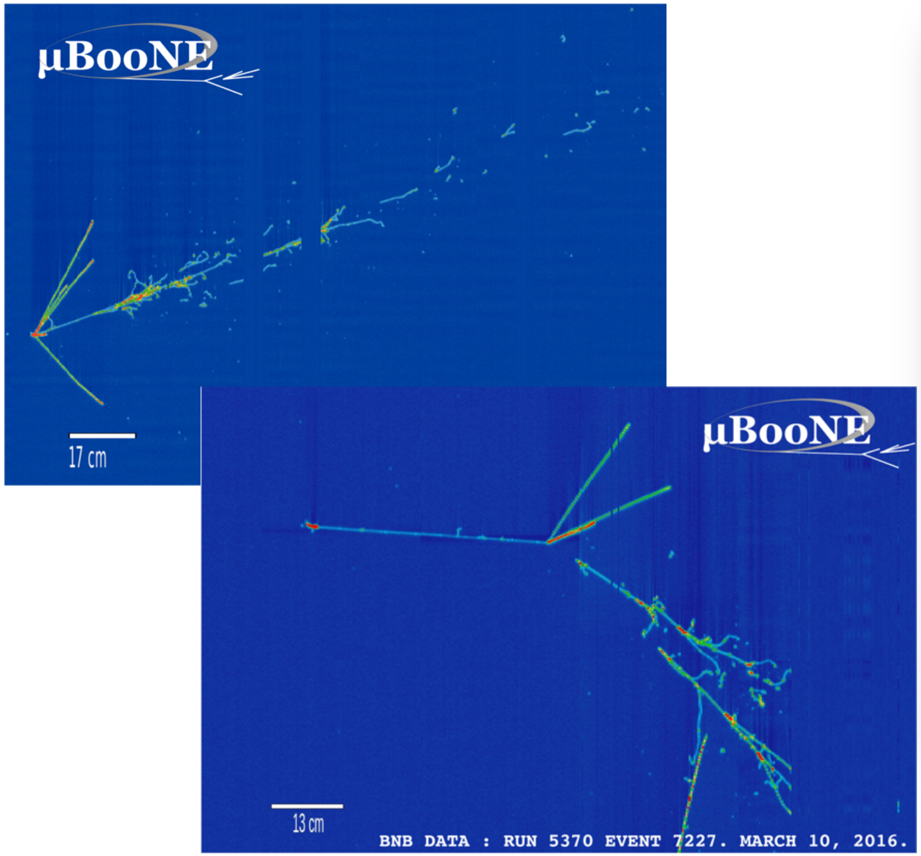


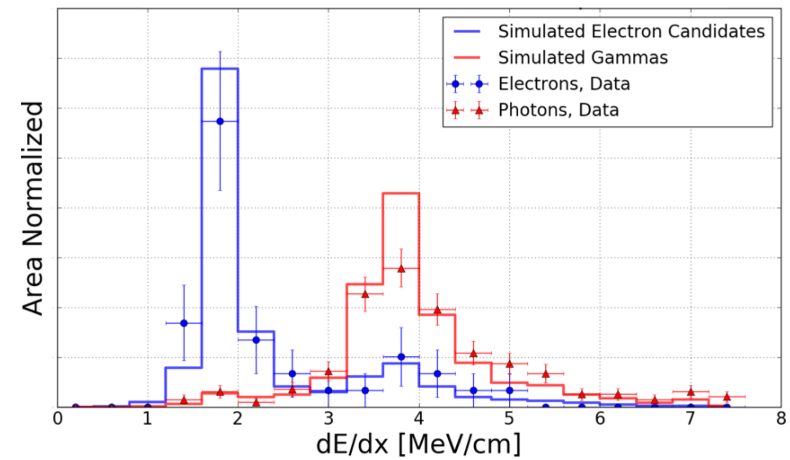
Cherenkov detector

Electron/Photon Separation

Neutrino events with γ are differentiated on the basis of:

1. Detached shower vertex from neutrino interaction vertex
2. Larger dE/dx deposited at the beginning of the shower (2 MIP vs 1 MIP)





ArgoNeuT
Phys. Rev. D 95, 072005 (2017).

Typical e/γ separation: ~90% → **Ideal technology for ν_e measurements**

MicroBooNE

Intermediate-scale liquid argon time projection chamber detector.
First large-scale LArTPC operating in the US!

Aims to demonstrate LArTPC technology (scalability and performance), and carry out a rich neutrino (and beyond) physics program!

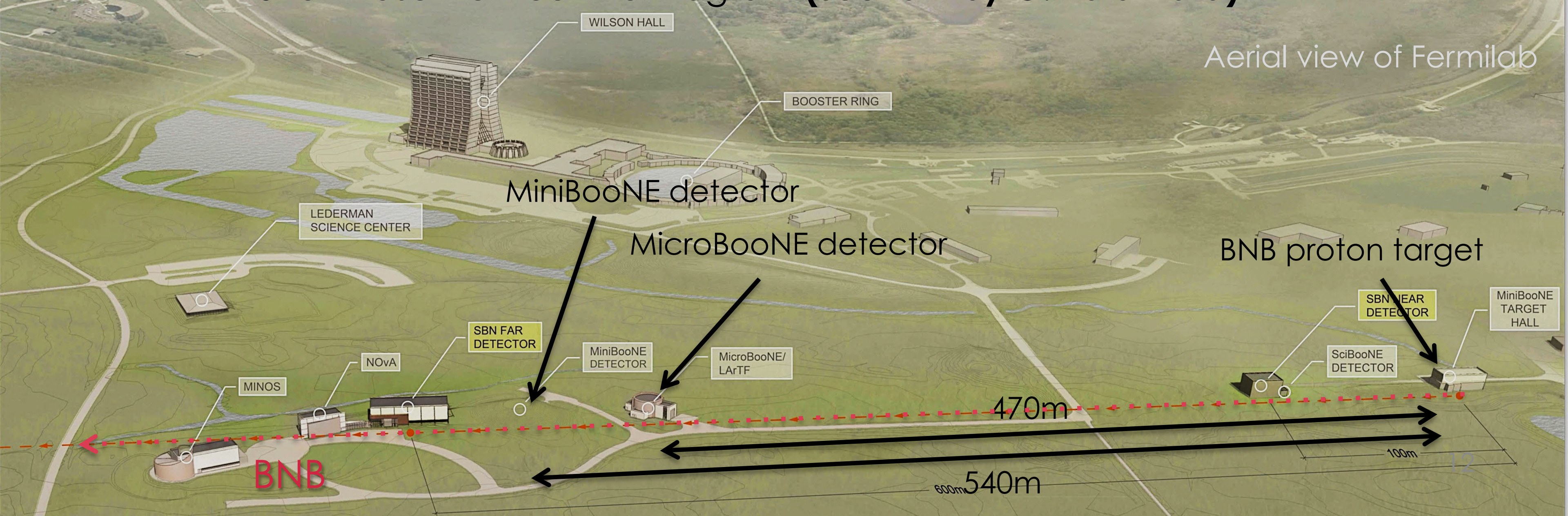
MicroBooNE

Intermediate-scale liquid argon time projection chamber detector.
First large-scale LArTPC operating in the US!

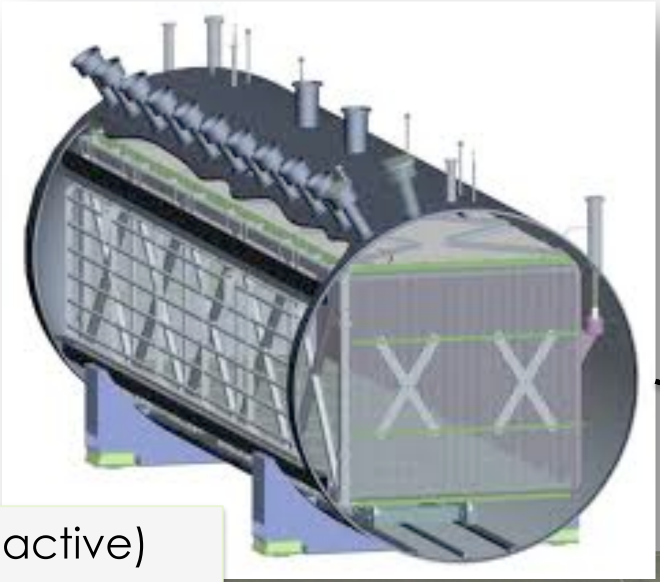
Situated in the Booster Neutrino Beamline, on-site at Fermilab, and just upstream of MiniBooNE (same neutrino beam, E~500 MeV, similar baseline L~500m).
Also views NuMI beam at off-axis.

Ideal experiment for:

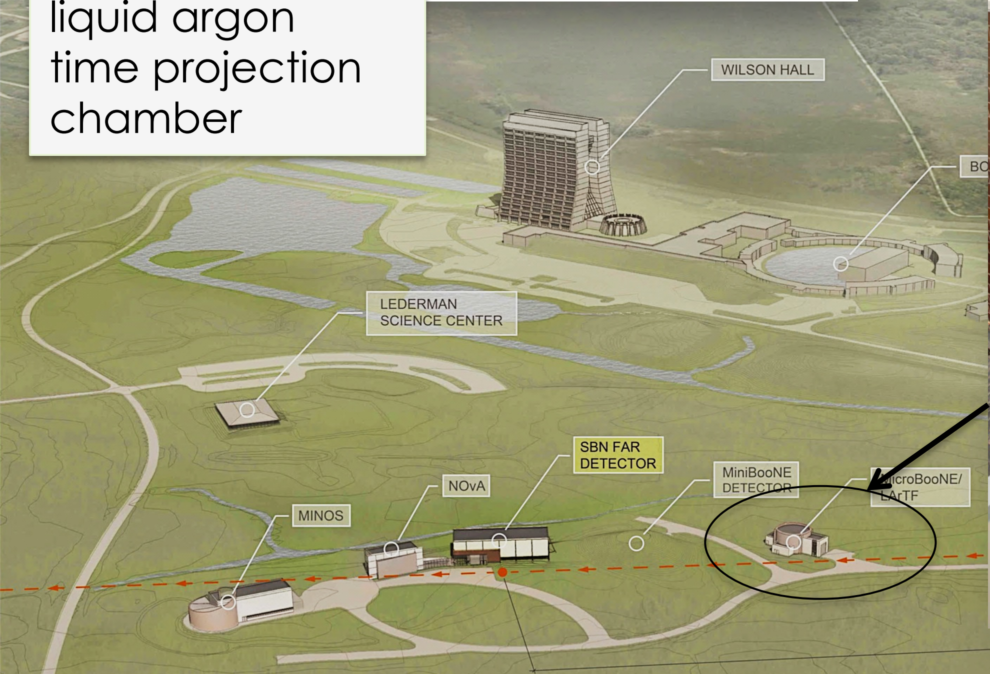
→ **investigating the MiniBooNE anomalous low energy excess**
→ **performing neutrino cross section measurements at E ~ a few hundred MeV**
→ constraining **light sterile neutrino** parameter space as part of the Short Baseline Neutrino Program **(see talk by O. Palamara)**



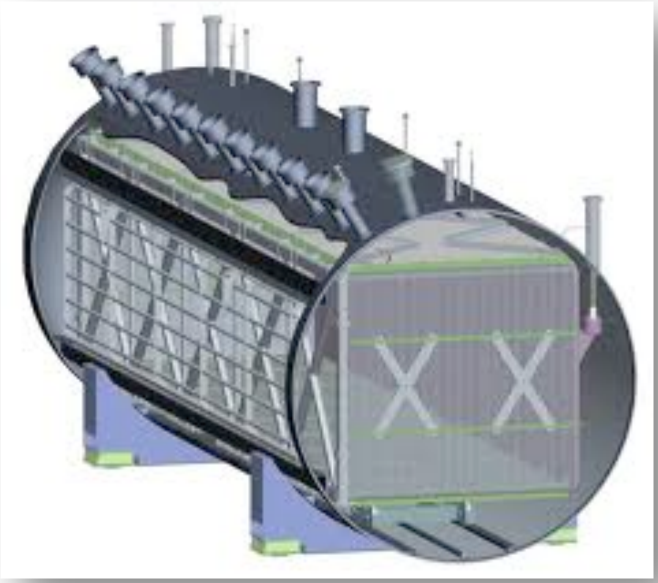
MicroBooNE



87 ton (active) liquid argon time projection chamber

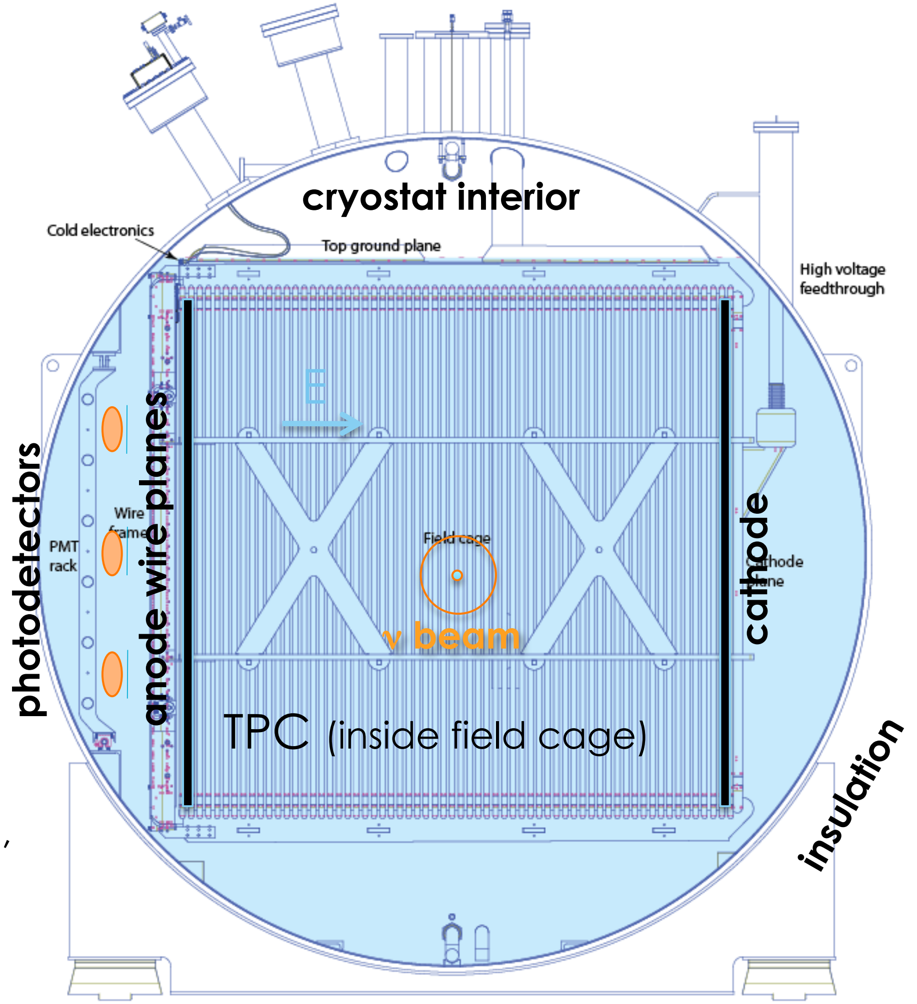


MicroBooNE Detector Parameters



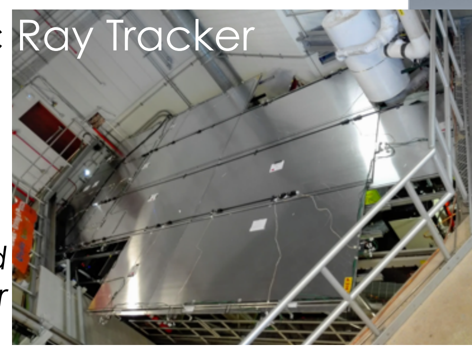
- 2.5 m x 2.3 m x 10.2 m TPC
- **170 (87) tons total (active) LAr mass**
- 2.5m drift length (~2ms drift time with -70kV on cathode)
- 3 wire planes (8,256 wires): 0°, ±60° from vertical, 3 mm wire separation
- 32 PMT's, for t_0/drift coordinate determination, and triggering for empty neutrino beam spill rejection

Cross section of detector:

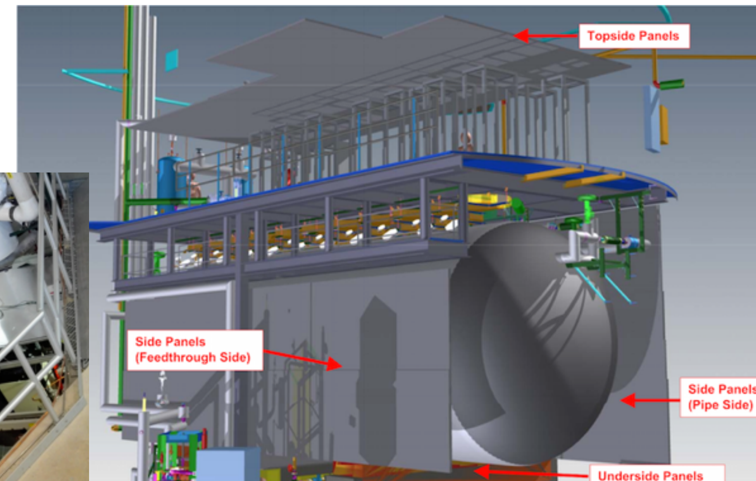


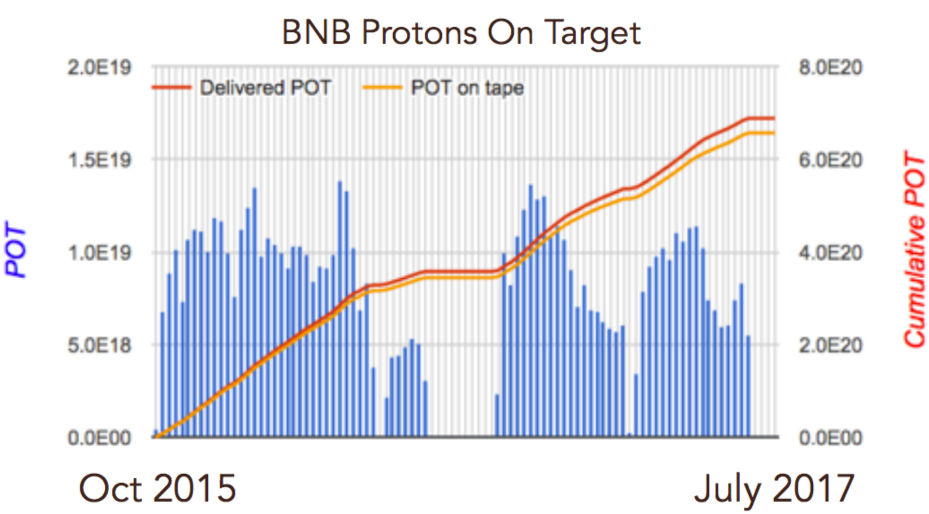
MicroBooNE Status

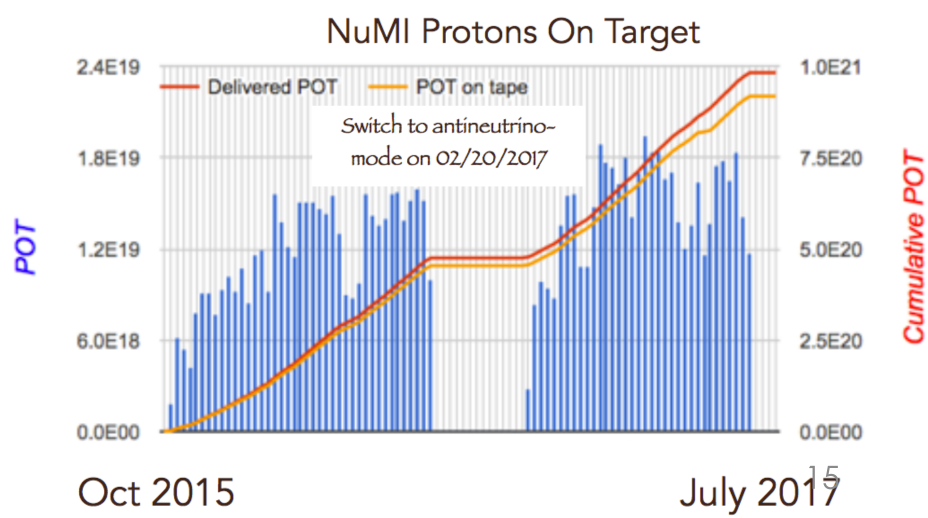
- Has been operational (with neutrino beam on) since Oct. 2015
- Has collected >6E20 POT to date from the BNB (~150,000 interactions)!
- Comparable event rate statistics also from the NuMI beam line (off axis)
- Has undergone several upgrades:
  - Continuous TPC readout for supernova searches (see later slides)
  - Installation of Cosmic Ray Tracker



CRT tracker installed around MicroBooNE detector

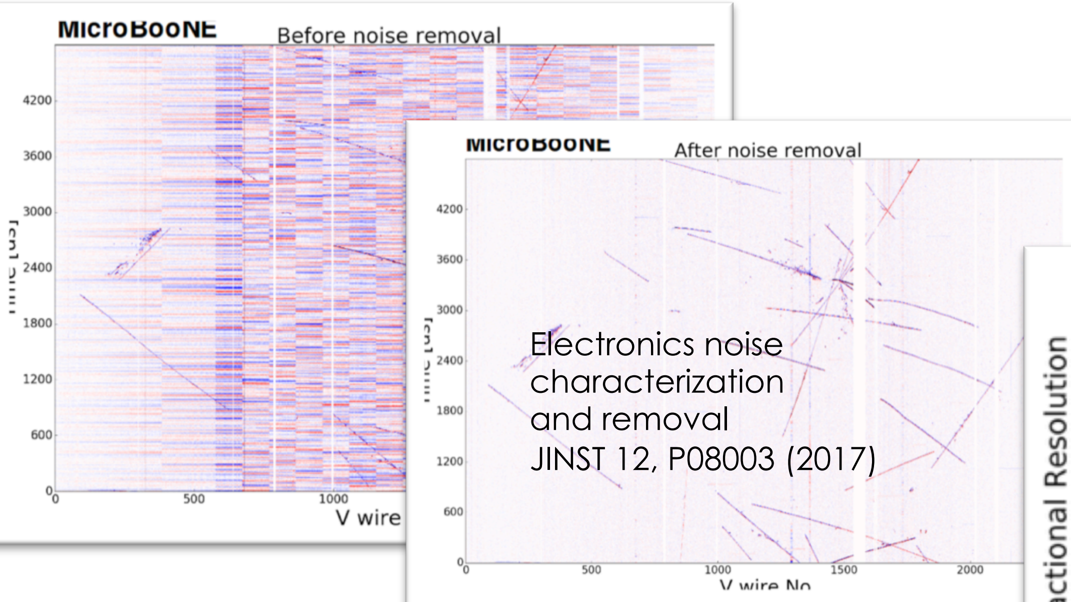


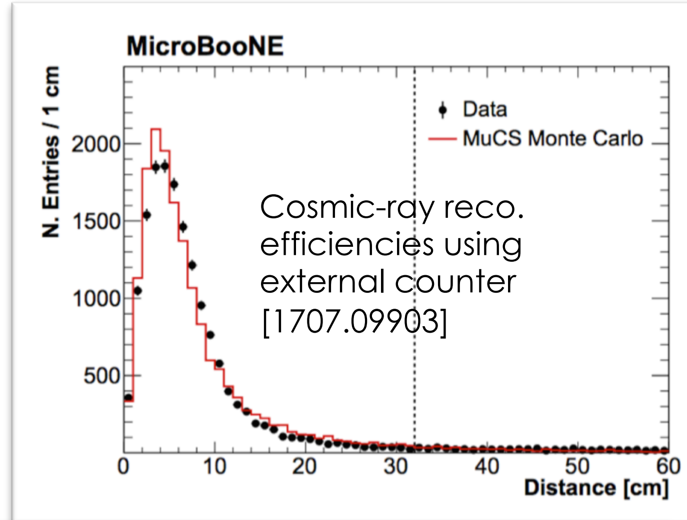


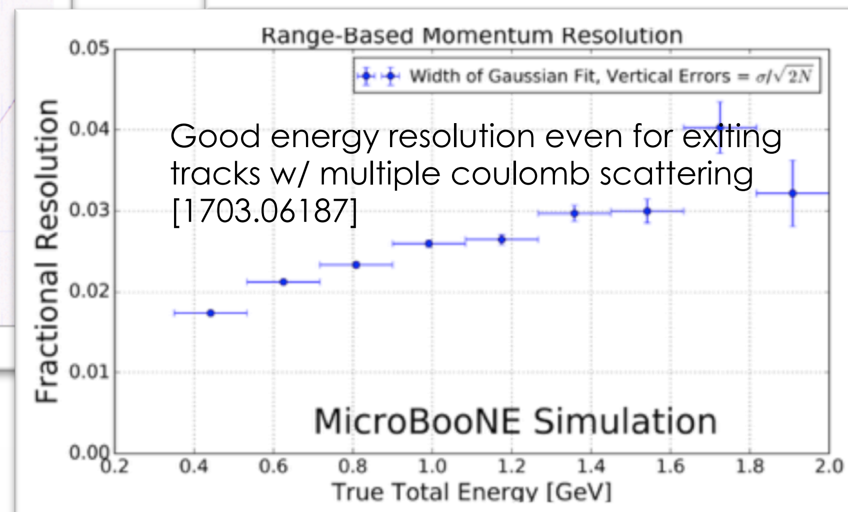


MicroBooNE Status

- **7 publications and 20 public notes!**
- **Many first results, more to come!**



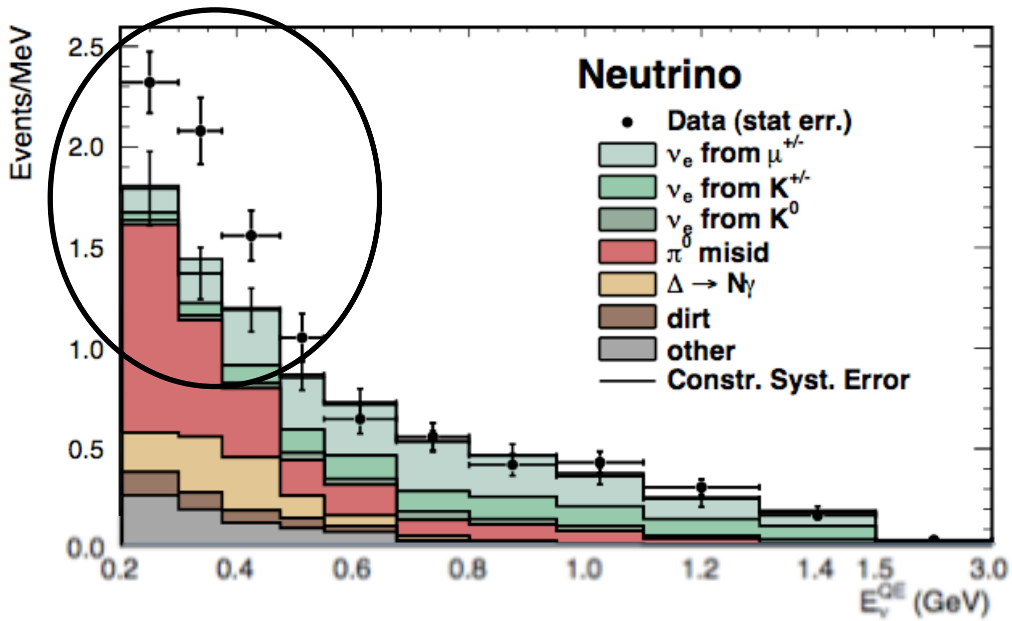




Publications by the MicroBooNE Collaboration:

- Public Notes page
- MicroBooNE collaboration, "The Pandora Multi-Algorithm Approach to Automated Pattern Recognition of Cosmic Ray Muon and Neutrino Events in the MicroBooNE Detector", arXiv:1708.03135, submitted to Eur. Phys. J. C.
- MicroBooNE collaboration, "Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter", arXiv:1707.09903, submitted to JINST
- MicroBooNE collaboration, "Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC", arXiv:1705.07341, JINST 12, P08003 (2017)
- MicroBooNE collaboration, "Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC", arXiv:1704.02927, JINST 12, P09014 (2017)
- MicroBooNE collaboration, "Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering", arXiv:1703.06187, submitted to JINST
- MicroBooNE collaboration, "Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber", arXiv:1611.05531, JINST 12, P03011 (2017)
- MicroBooNE collaboration, "Design and Construction of the MicroBooNE Detector", arXiv:1612.05824, JINST 12, P02017 (2017)

MicroBooNE Physics Goals:
1) Investigation of MiniBooNE anomalous low energy excess

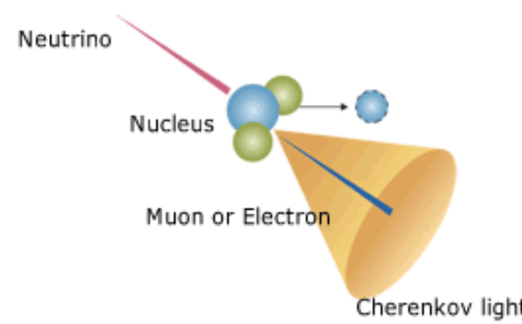


PRL 102, 101802 (2009)

Neutrino mode:
Excess: 162.0 $\pm$ 47.8 (3.4σ)

Antineutrino mode:
Excess: 78.4 $\pm$ 28.5 (2.8σ)

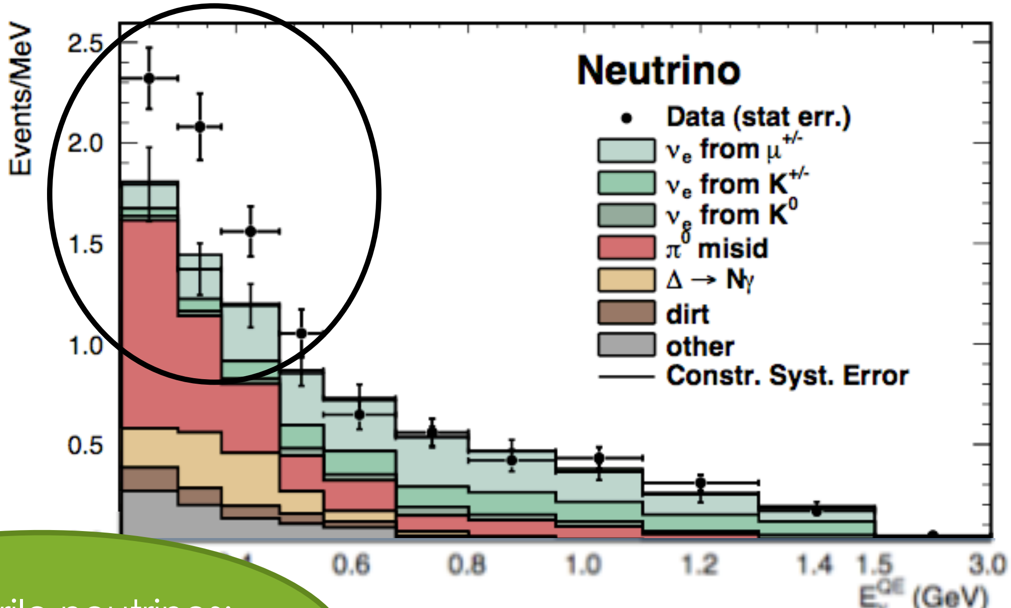
Combined:
Excess: 240.3 $\pm$ 34.5 $\pm$ 53.6
3.8σ significance



MiniBooNE anomalous low energy excess:
Excess of ν_e CCQE-like events observed in the MiniBooNE cherenkov detector, in a ν_μ-dominated beam, at L/E ~ 1m/MeV

Multiple interpretations have been put forward… yet inconclusive…

MicroBooNE Physics Goals:
1) Investigation of MiniBooNE anomalous low energy excess



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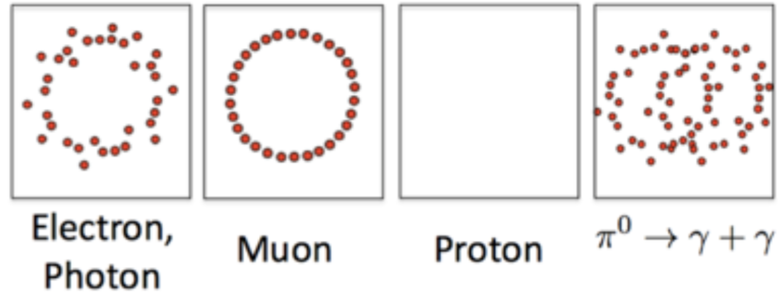
Light sterile neutrinos: Unaccounted ν_e /ν_μ disappearance?

Energy reconstruction? Cross-section/nuclear effects?

Electron-like new background?

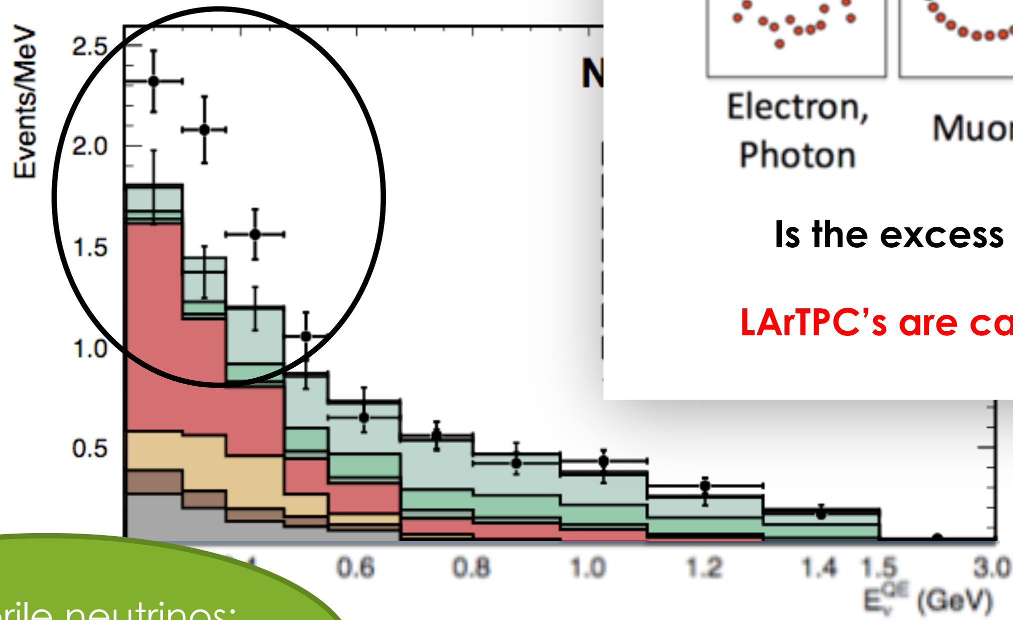
Single-photon new background?

MicroBooNE Physics Goals:
1) Investigation of MiniBooNE anom



Is the excess electrons, or photons?

LArTPC's are capable of e/γ separation!



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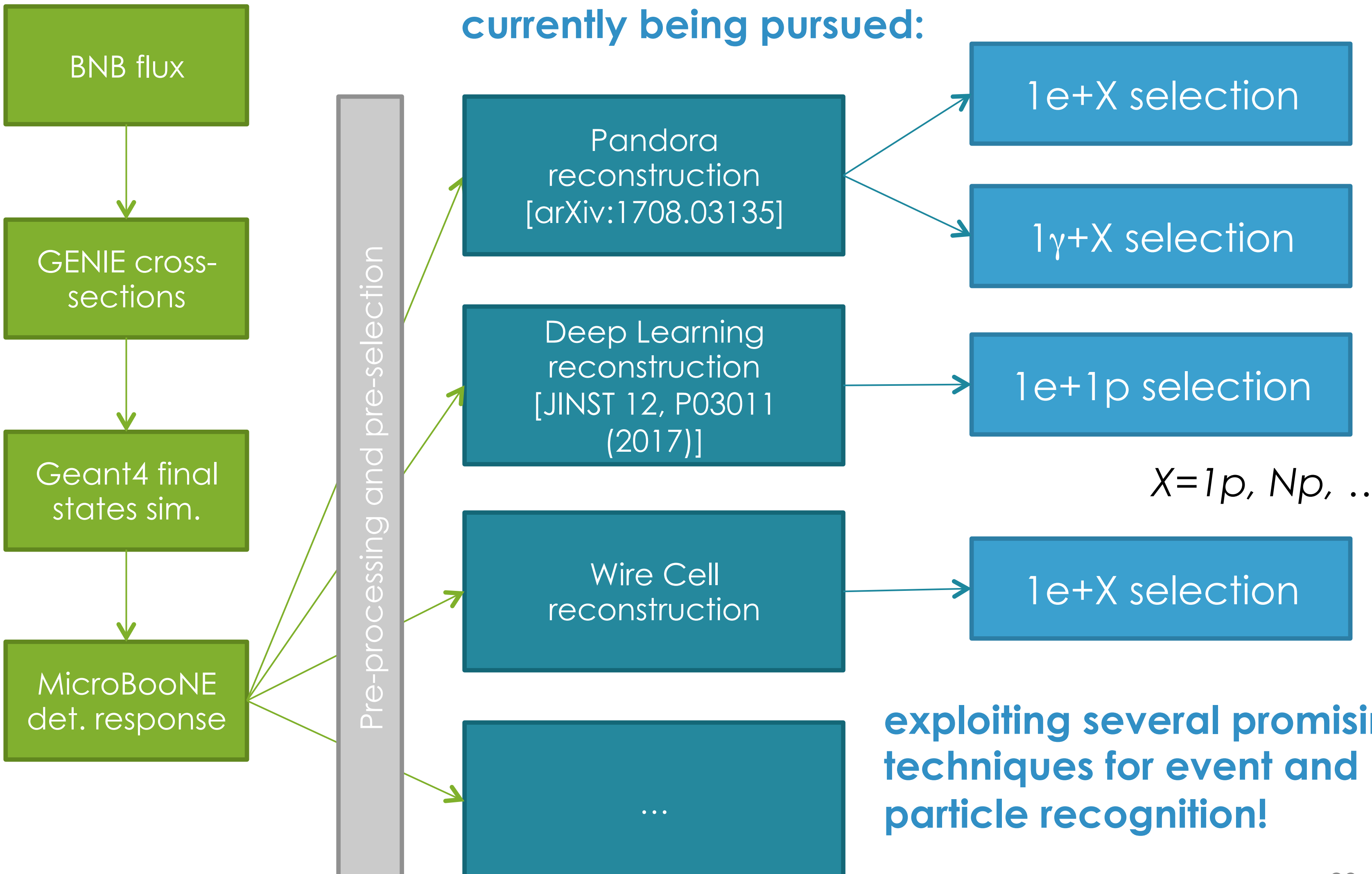
MicroBooNE Physics Goals:
1) Investigation of MiniBooNE anomalous low energy excess

Multiple, semi-independent analyses currently being pursued:



exploiting several promising techniques for event and particle recognition!

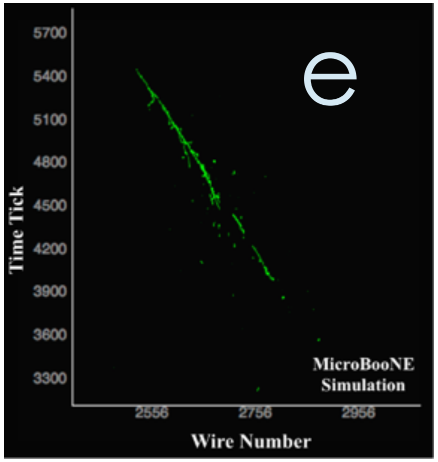
MicroBooNE Physics Goals:
1) Investigation of MiniBooNE anomalous low energy excess

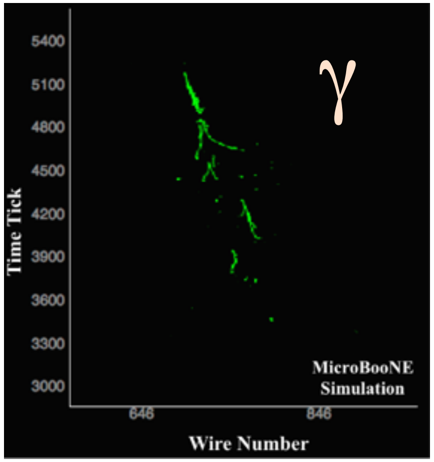
E.g. using deep-learning-based reconstruction

Using Convolutional Neural Networks → a revolutionary image analysis technique! → Well suited for LArTPC's!

Successful in identification and differentiation among different particle types.

[JINST 12, P03011 (2017)]





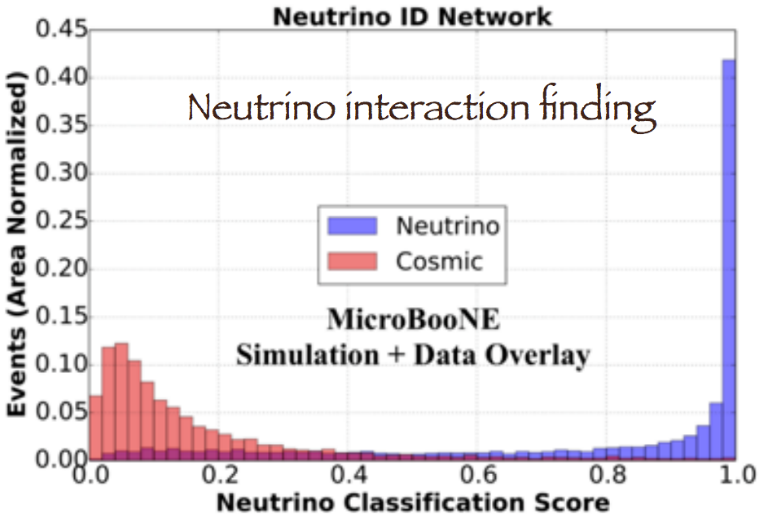
Sample	Electron	Photon	Muon	Pion	Proton
Detection Accuracy (%)	77.8 +/- 0.7	83.4 +/- 0.6	89.7 +/- 0.5	71.0 +/- 0.7	91.2 +/- 0.5
Most Frequent MisID (%)	γ (19.9)	e^- (15.0)	π^- (5.4)	μ^- (22.6)	μ^- (4.6)

MicroBooNE Physics Goals:
1) Investigation of MiniBooNE anomalous low energy excess

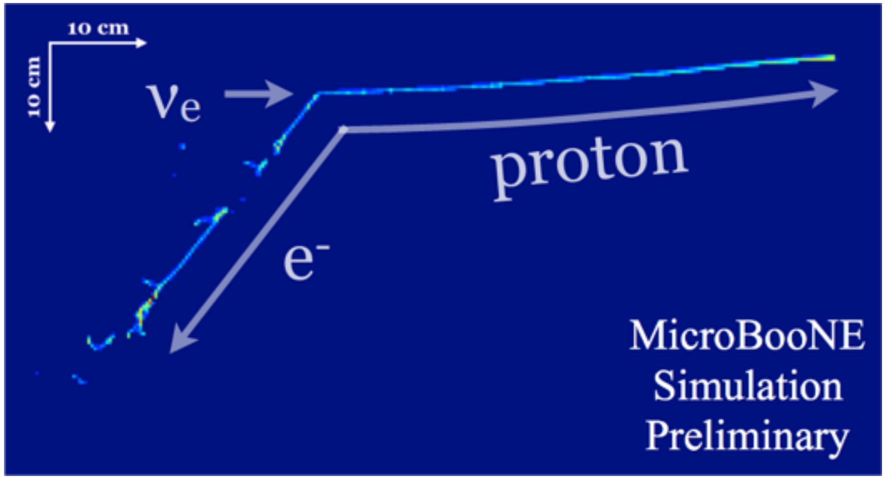
E.g. using deep-learning-based reconstruction

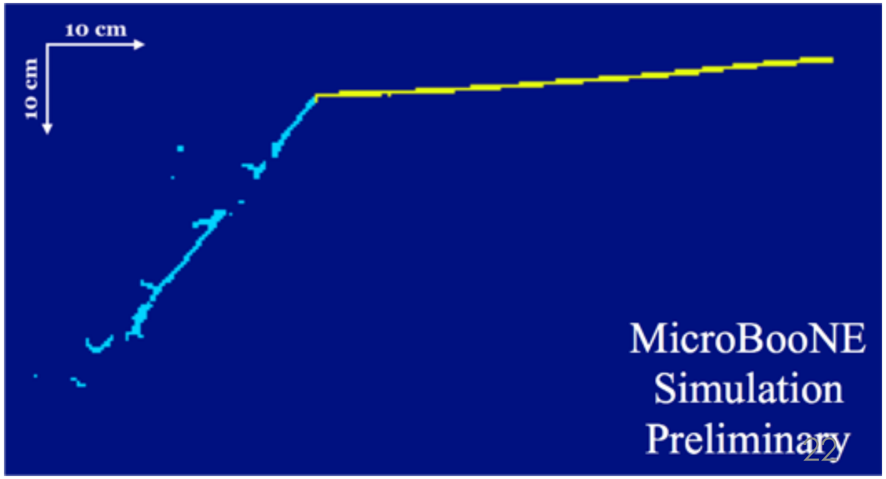
Also capable of:
- Neutrino interaction finding
- Neutrino interaction ID
- Neutrino vertex finding

[JINST 12, P03011 (2017)]



Ongoing efforts toward 1e + 1p selection:



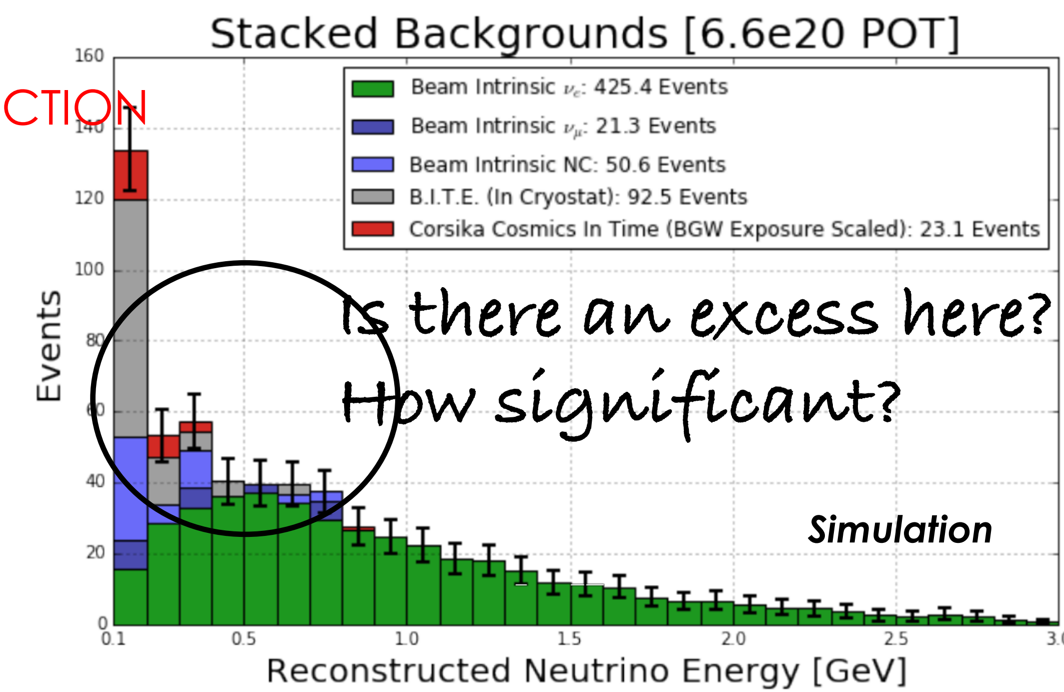


MicroBooNE Physics Goals:
1) Investigation of MiniBooNE anomalous low energy excess

Ultimately, all LEE analyses aim to maximize sensitivity to an excess above background prediction:

D. Kaleko, MicroBooNE FERMILAB-THESIS-2017-12

Example:
EMULATED RECONSTRUCTION
of 1e+np sample



If excess is observed,
is it consistent with MiniBooNE?

Need to know: under which interpretation assumption(s)?

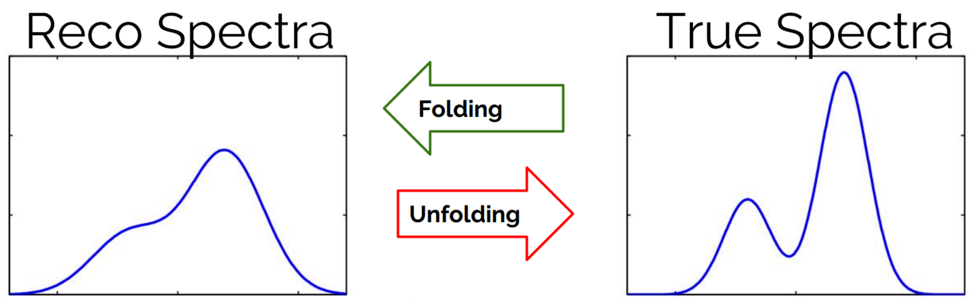
MicroBooNE Physics Goals:
1) Investigation of MiniBooNE anomalous low energy excess

Ongoing, joint effort with MiniBooNE collaboration:

Unfolding observed MiniBooNE excess into "underlying model prediction" for MicroBooNE

Given a model assumption:

- Derive MiniBooNE ν_e CCQE reconstruction and selection Response Matrix "A"
- Unfold observed excess into raw prediction; unfolding methods
  - Singular Value Decomposition unfolding
  - D'Agostini Iterative Bayesian Unfolding
- Extract "correction function" for first-principles MonteCarlo prediction in MiniBooNE → "model"
- Apply model in MicroBooNE simulation



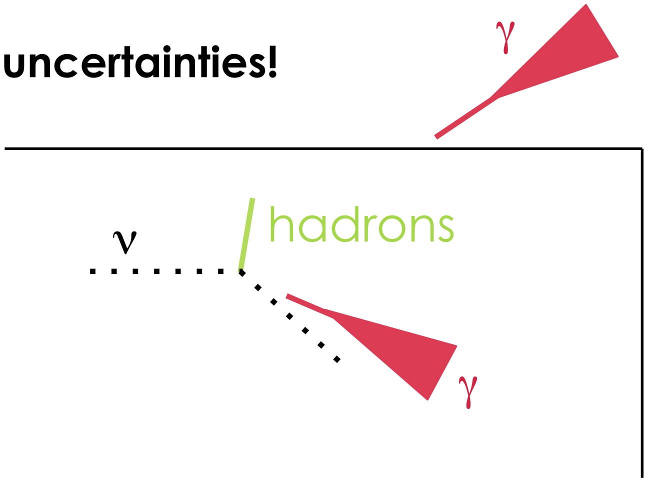
r_i : Reconstructed MC spectra (n_r), t_α : True MC spectra (n_t),

$$\boxed{r = At \quad \Leftrightarrow \quad r_i = \sum_{\alpha=0}^{n_t} A_{i\alpha} t_\alpha}$$

A contains all detector, reconstruction and CCQE selection efficiencies and effects. Constructed using MiniBooNE Monte Carlo.

MicroBooNE Physics Goals:
1) Investigation of MiniBooNE anomalous low energy excess

Excess significance: Need also to consider systematic uncertainties!



– Constraining rate and overall uncertainty on mis-identified backgrounds:
  - NC π^0
  - TPC-external neutrino interactions
  - cosmogenic interactions

– For e-like low energy searches:
  Constraining intrinsic background rate and overall uncertainty by way of measuring ν_μ CC event rates (flux x cross-section)

Need independent (signal-blind) samples to validate simulation (flux, cross-section, detector performance), reconstruction, analysis methods…

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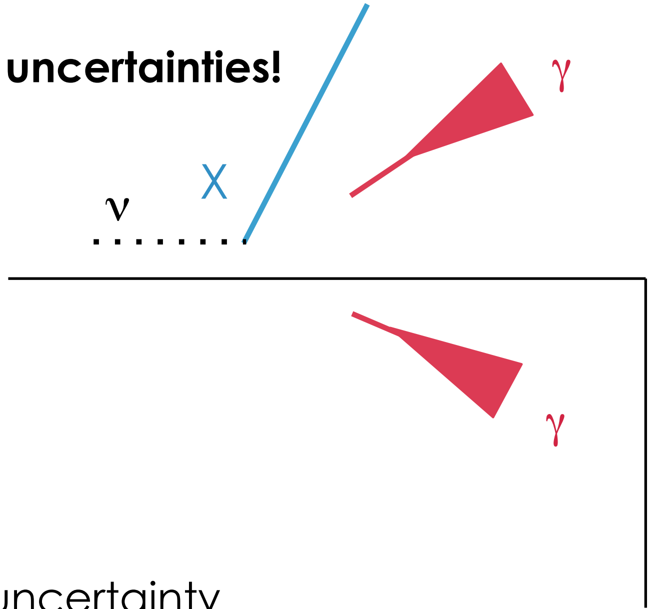

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MicroBooNE Physics Goals:
1) Investigation of MiniBooNE anomalous low energy excess

E.g. using Pandora-based reconstruction

Pandora: a multi-algorithm approach to automated pattern recognition for LArTPC detectors

O(100) specific-task/topology-tailored algorithms used to build an event

PandoraSDK provides the software infrastructure to manage the algorithm chain

[Eur. Phys. J. C 75, No. 9, 439 (2017)]

Ongoing efforts toward 1e + X selection and 1γ + X selection.
Focusing on 1μ + 1p selection; offers valuable cross-check and constraint…

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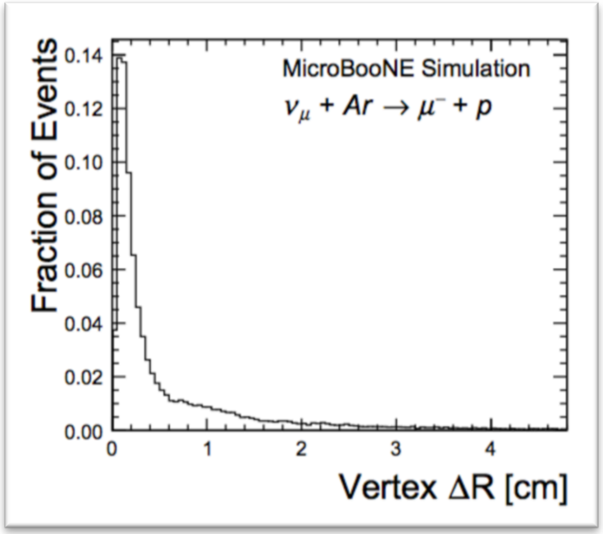

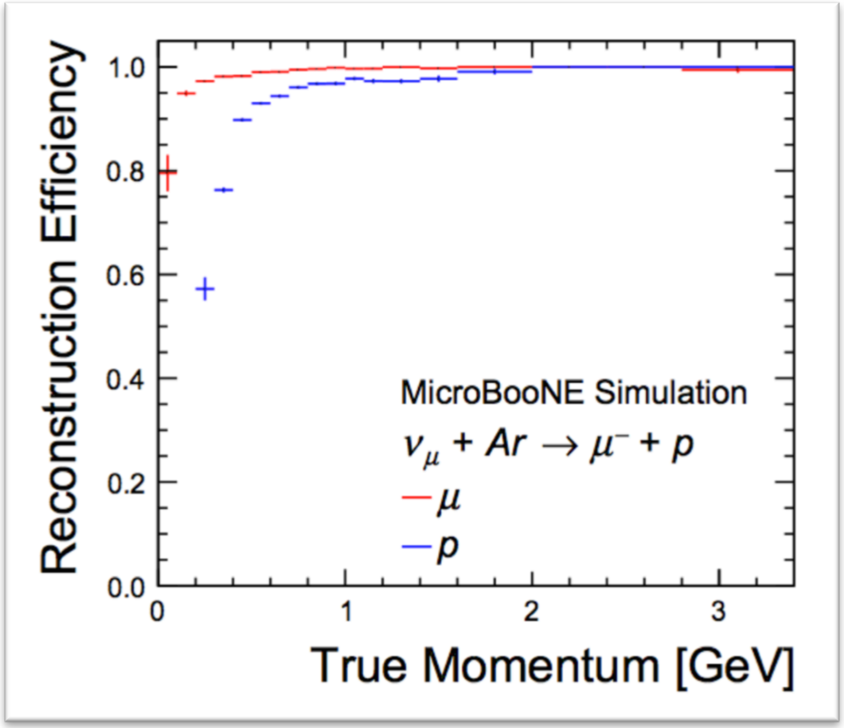

ν_μ CCQE → 1μ + 1p

#Matched Particles	0	1	2	3+
μ	1.3%	95.8%	2.9%	0.1%
p	8.9%	87.3%	3.6%	0.2%

[arXiv:1708.03135]

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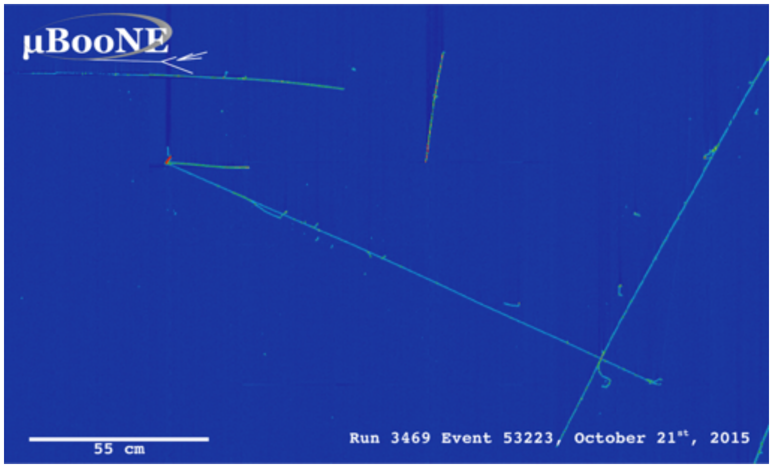
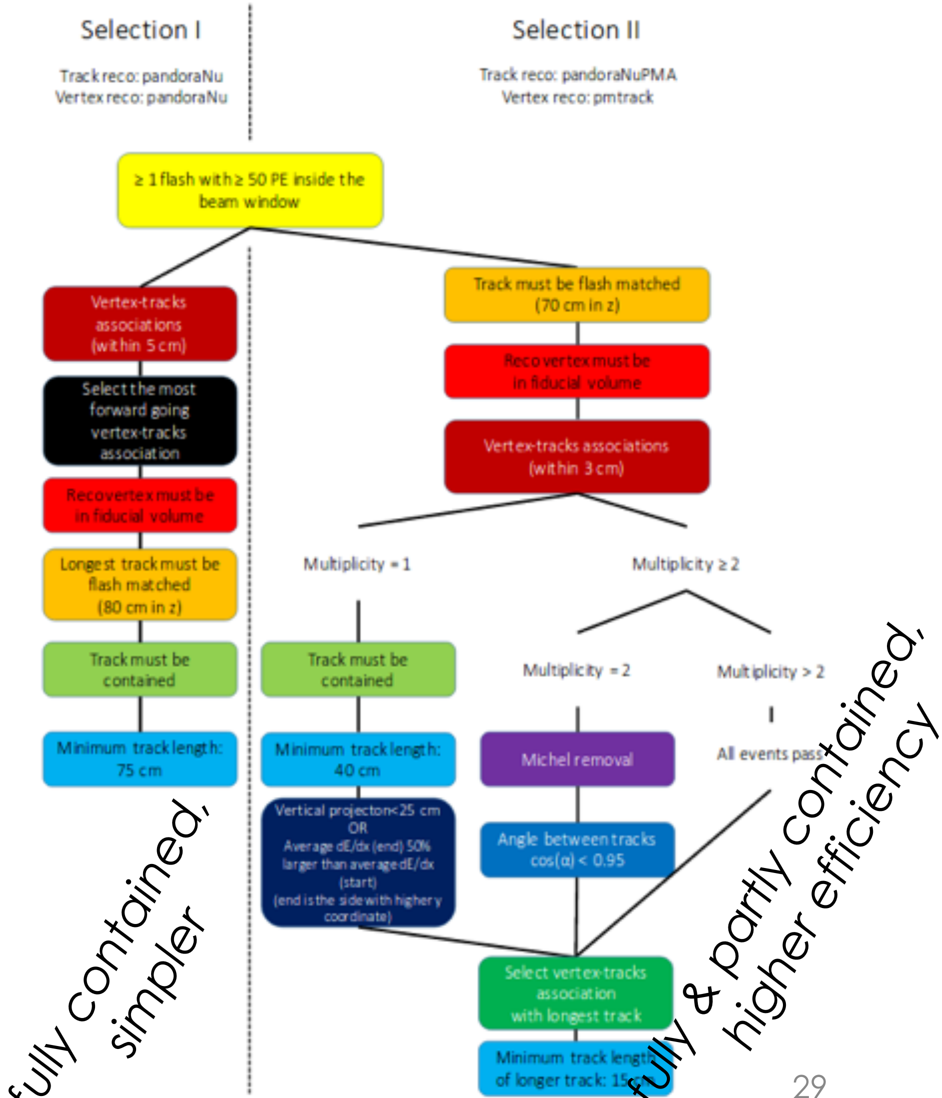
Focusing on 1μ + 1p selection; offers valuable cross-check and constraint…

MicroBooNE Physics Goals:
2) Neutrino cross-section measurements

Validating simulation and reconstruction using an (un-blinded) muon selection sample:





E.g. Pandora-based reconstruction

Initial efficiency and purity:
30% Eff. at 65% Purity

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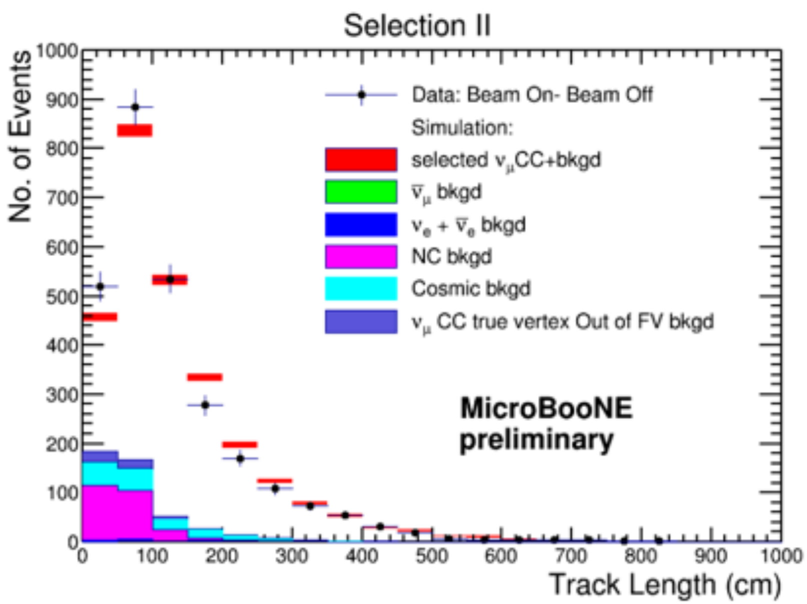
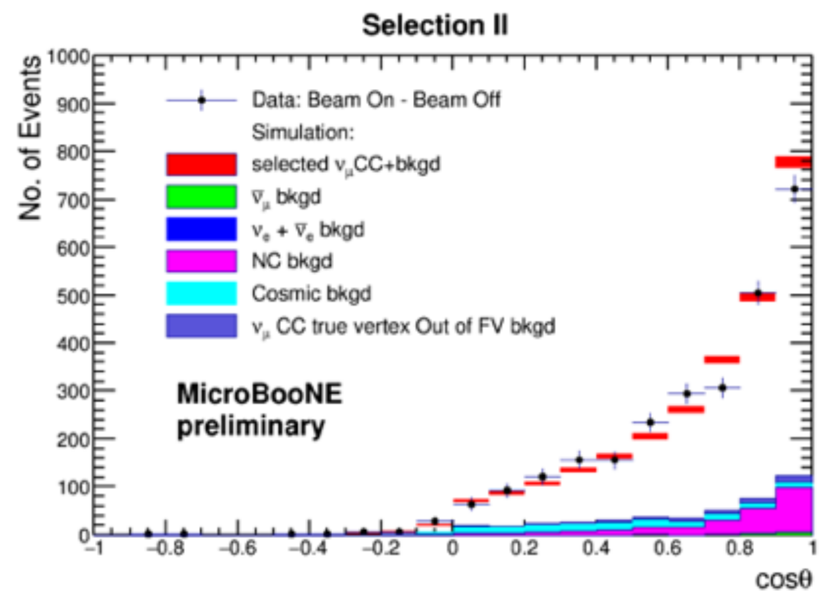




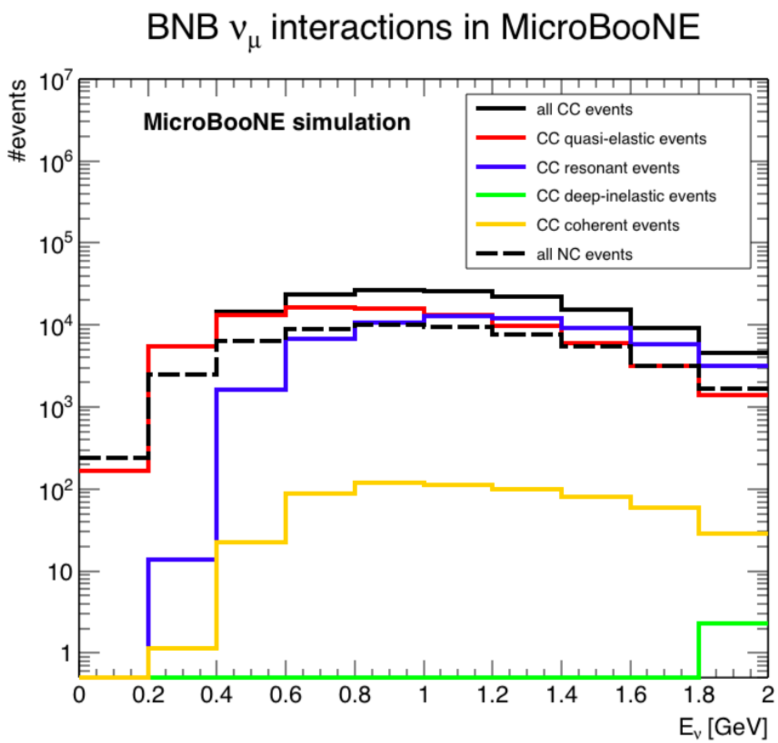
E.g. Pandora-based reconstruction

Initial efficiency and purity:
30% Eff. at 65% Purity

- Shape-normalized event rates.
- Demonstrates data/MC agreement, and **enables CC inclusive cross-section measurement!**

MicroBooNE Physics Goals:
2) Neutrino cross-section measurements

>150,000 ν_μ CC inclusive interactions expected!
Energy range relevant for future experiments, e.g. DUNE.
Energy regime probes physics at nucleon level (e.g. nucleon correlations) and much more…



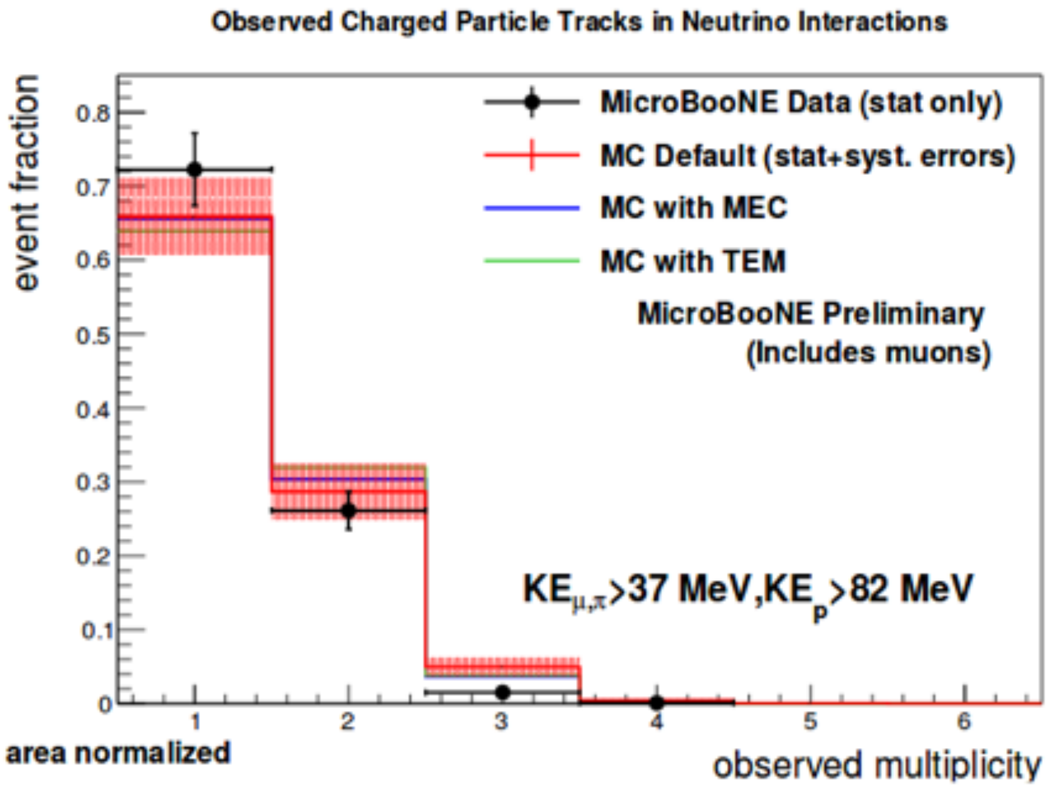
6.6e20 POT (~3 years)

	numu	numubar	nue	nuebar
CC Total	173302	1407	1469	36
CC - QE	95296	773	729	17
CC – RES	75657	604	702	18
CC – DIS	1607	1.3	29	0.5
CC - COH	740	29	8.5	0.7
NC Total	64661	1002	502	17
NC - QE	35951	633	254	7.0
NC - RES	27665	358	236	9.4
NC - DIS	519	1.3	8.8	0.2
NC - COH	525	10	3.2	0.6

*Expected rates for 6.6E20 POT (2-3 years of running), not efficiency weighted.

MicroBooNE Physics Goals:
2) Neutrino cross-section measurements

Measurements of ν_μ CC inclusive final state multiplicity:



Starting with **Pandora-based Selection I** (fully contained interactions):

Additional **track/vertex quality** requirements (collection plane)

Fit neutrino and cosmic-ray contributions across 4 samples of varying purity.

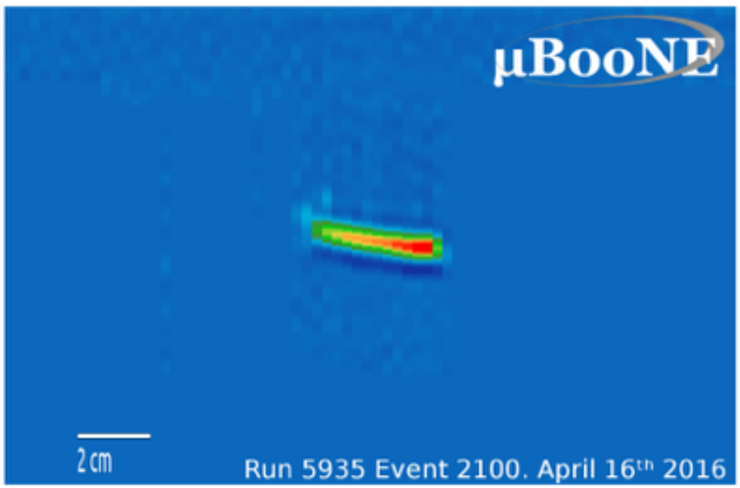
Count tracks associated with vertex (ignore showers)

**Includes detector, reconstruction, and selection efficiency; backgrounds; all-final-state-track-inclusive. Systematic uncertainties are preliminary.*

Nice data/MC agreement with several GENIE tunes!

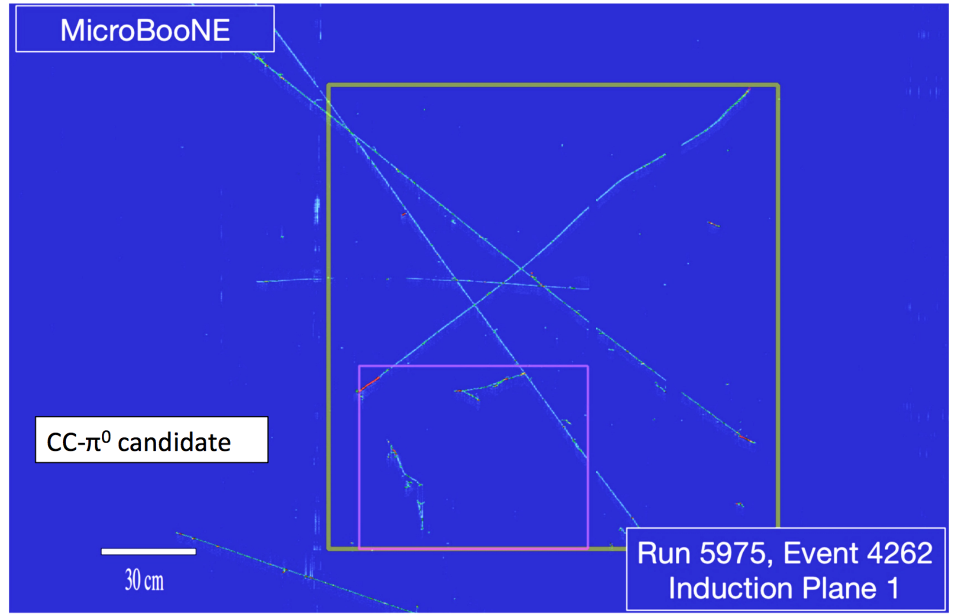
MicroBooNE Physics Goals:
2) Neutrino cross-section measurements

Other ongoing cross-section analyses:



NC elastic (proton) channel

~20k events on tape!
Lower proton threshold compared to fine-grained scintillator detectors

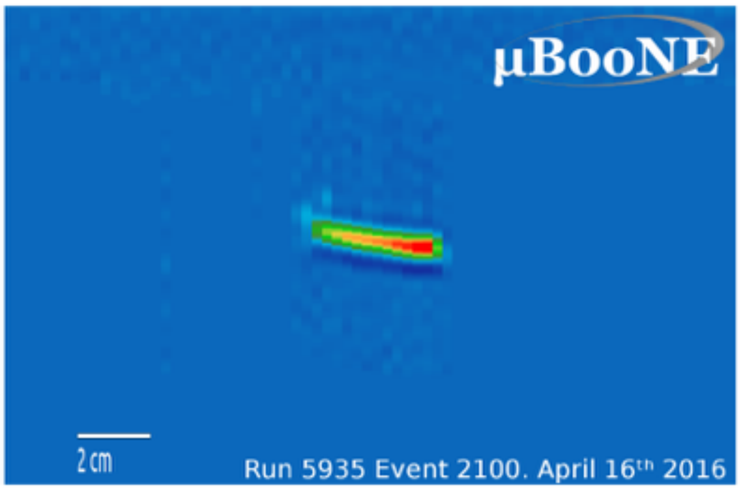


CC π^0 channel

~10k events on tape!
Important for understanding π^0 mis-identification for low energy excess and oscillation analyses

MicroBooNE Physics Goals:
2) Neutrino cross-section measurements

Other ongoing cross-section analyses:



NC elastic (proton) channel

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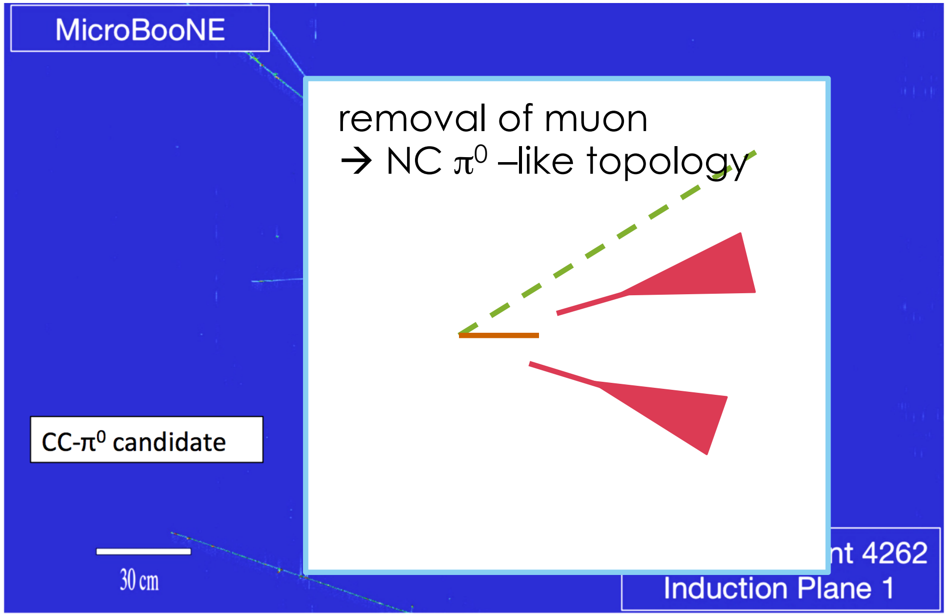


CC π^0 channel

~10k events on tape!
Important for understanding π^0 mis-identification for low energy excess and oscillation analyses

MicroBooNE Physics Goals:
3) Astro-particle and exotic physics

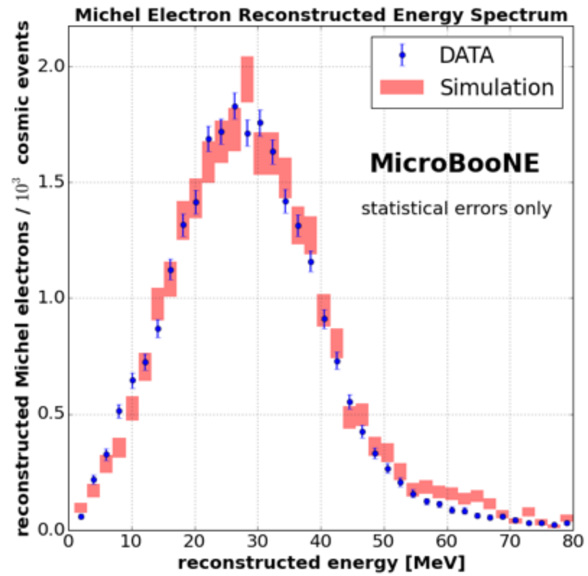
Planned searches for:

- Heavy sterile neutrinos
- Dark matter, in BNB beam-dump configuration

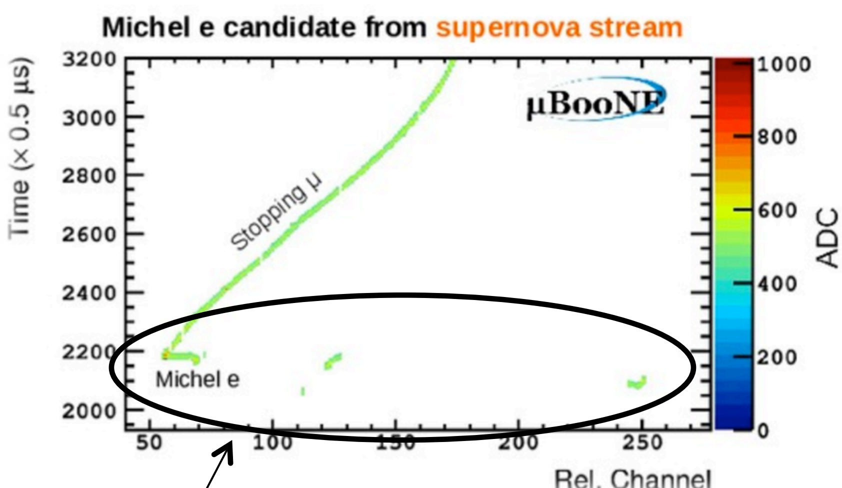
Sensitivity studies and proof-of-principle searches for

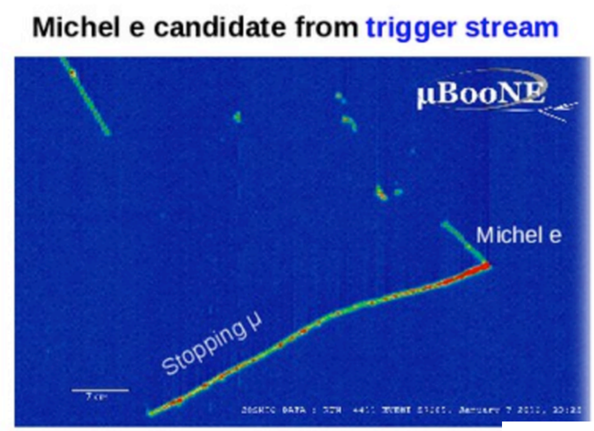
- Supernova core-collapse neutrino interactions (~10 MeV)
- Neutron-antineutron oscillation, p→Kν decay, and other baryon-number-violating signatures

Michel Electrons from stopping cosmic muons offer a calibration source for low-energy electromagnetic activity.



[JINST 12, P09014 (2017)]





Michel e candidate recorded in lossy-compression stream (dynamic zero suppression)

Summary

MicroBooNE now:

- MicroBooNE has been running in the BNB since Oct. 2015
- Has collected almost (~90%) full dataset necessary for carrying out an investigation of MiniBooNE anomalous excess
- Demonstrating stable operation of large-scale LArTPC's, and promising performance on automated reconstruction, particle- and event-ID.

~1 year timescale:

- Several analyses ongoing (MiniBooNE low energy excess, neutrino-argon interaction cross-sections, astro-particle/exotic physics)
- More results to come!

~few years timescale:

- And as part of the SBN program, MicroBooNE will explore sterile neutrino oscillations with unprecedented sensitivity during the next five years!