



# New Results from MicroBooNE

**Pip Hamilton**

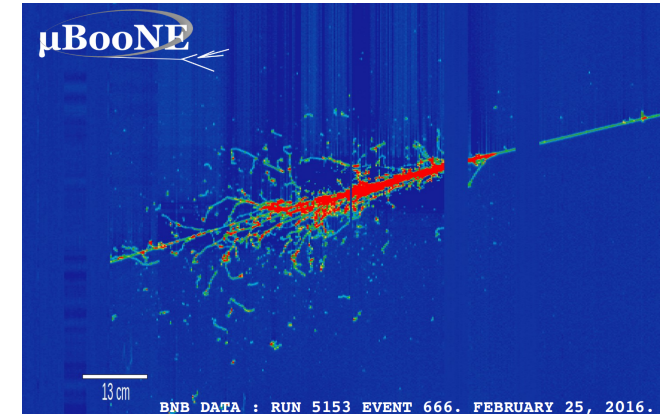
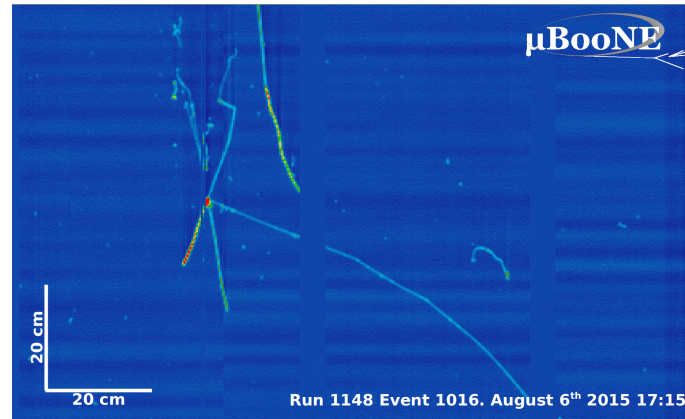
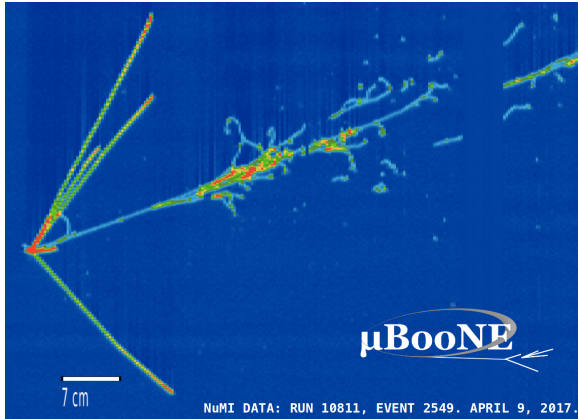
on behalf of the MicroBooNE collaboration

# Overview

- **MicroBooNE's Physics Mission**
  - LArTPC Reconstruction
  - Cross-Section Studies
  - Seeking the Low-Energy Excess
- **New Neutrino Cross-Section Results**
  - Charged Particle Multiplicity Study
  - Charged Current  $\pi^0$  Cross-Section
  - Charged Current Inclusive Cross-Section
- **Progress Towards  $\nu_e$  Appearance**
- **Conclusions**

# MicroBooNE's Physics Mission

# LArTPC Reconstruction



- LArTPCs give bubble chamber-like image resolution, with much higher data rates (at short baselines).
  - Images of interactions have lots of fine detail features.
  - Reconstruction must be automated.
- MicroBooNE provides LArTPC data of the volume and quality needed to develop reconstruction techniques for future LArTPC neutrino detectors (e.g. SBND, DUNE).
  - Shared LArSoft reconstruction software.
- MicroBooNE uses multiple reconstruction approaches to explore which techniques are optimal for neutrino interaction analyses.

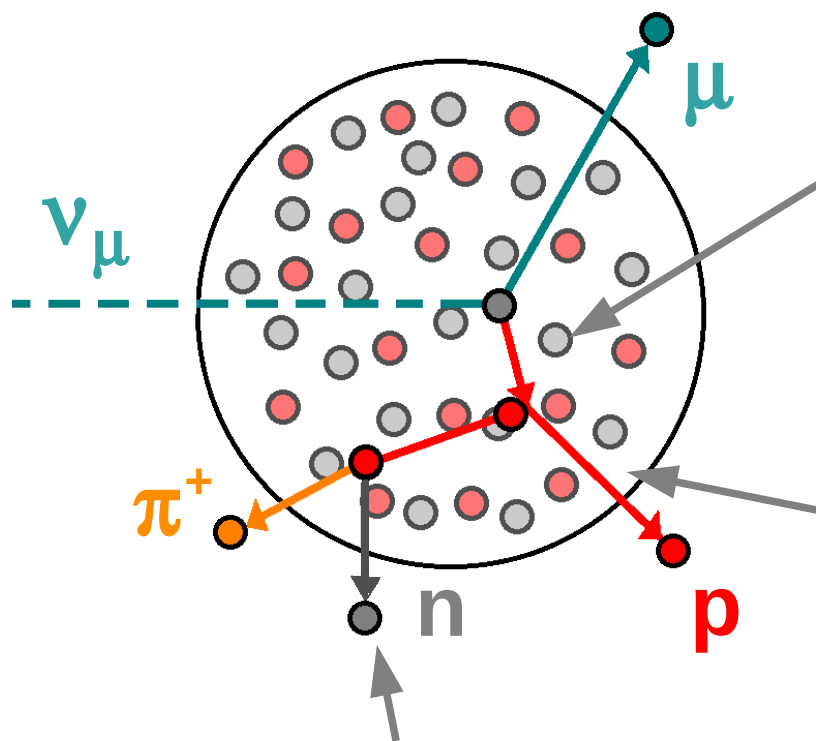
—► **Wire Cell**

—► **Pandora**

—► **Deep Learning**

# Cross-Section Studies

Larger detectors such as DUNE (and longer exposures on existing experiments such as NOvA and T2K) are moving us ever further into the systematically limited regime of neutrino oscillation measurements.



What was the momentum of the target nucleon?

Does  $\Sigma p$  at the  $\nu$  vertex =  $\Sigma p$  of the particles escaping the nucleus?

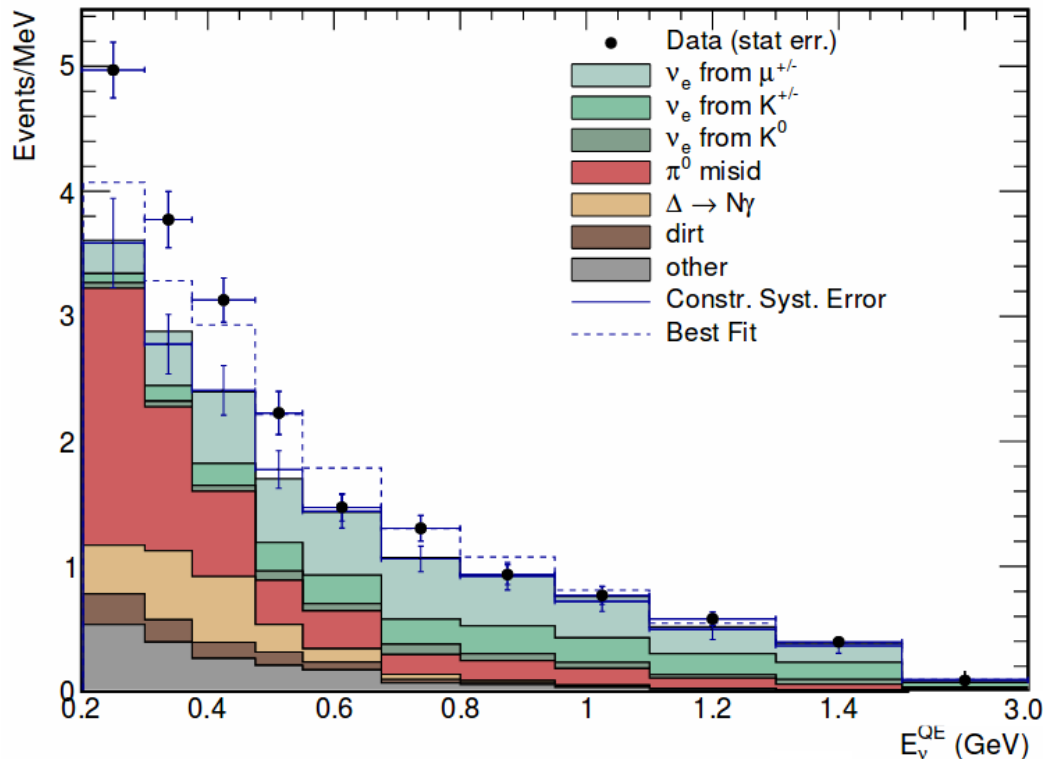
How many neutral particles carry energy away unseen?

Reconstructing the neutrino energy is highly dependent on our understanding of neutrino-nucleus cross-sections.

MicroBooNE offers the opportunity to perform high-statistics cross-section measurements on Ar.

- High resolution imaging  $\Rightarrow$  access to many exclusive channels, providing strong test of nuclear models.
- Comparative lack of data on Ar.
- Ar is a large nucleus!

# Seeking the Low-Energy Excess



The MiniBooNE neutrino mode data, showing the persistent excess at  $E_v^{QE} < 0.5$  GeV.

- The MiniBooNE low-energy excess is not going away.
  - $\nu_e$  appearance at short baseline  $\Rightarrow$  sterile neutrinos  $\Rightarrow$  new physics?
- MicroBooNE sits in the same beam, at approximately the same baseline.
- With LArTPC imaging capabilities, MicroBooNE has an enhanced ability to distinguish backgrounds.

Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment, [arXiv:1805.12028](https://arxiv.org/abs/1805.12028)

# New Cross-Section Results from MicroBooNE

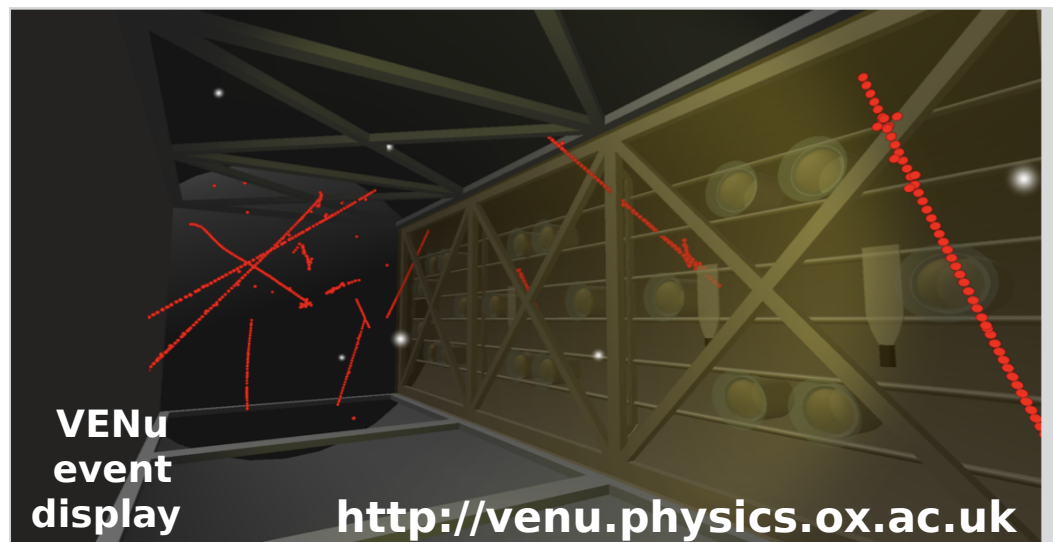
# New Cross-Section Results

MicroBooNE has recently produced 3 cross-sections:

- Charged Particle Multiplicity
- $CC-\pi^0$
- CC-inclusive

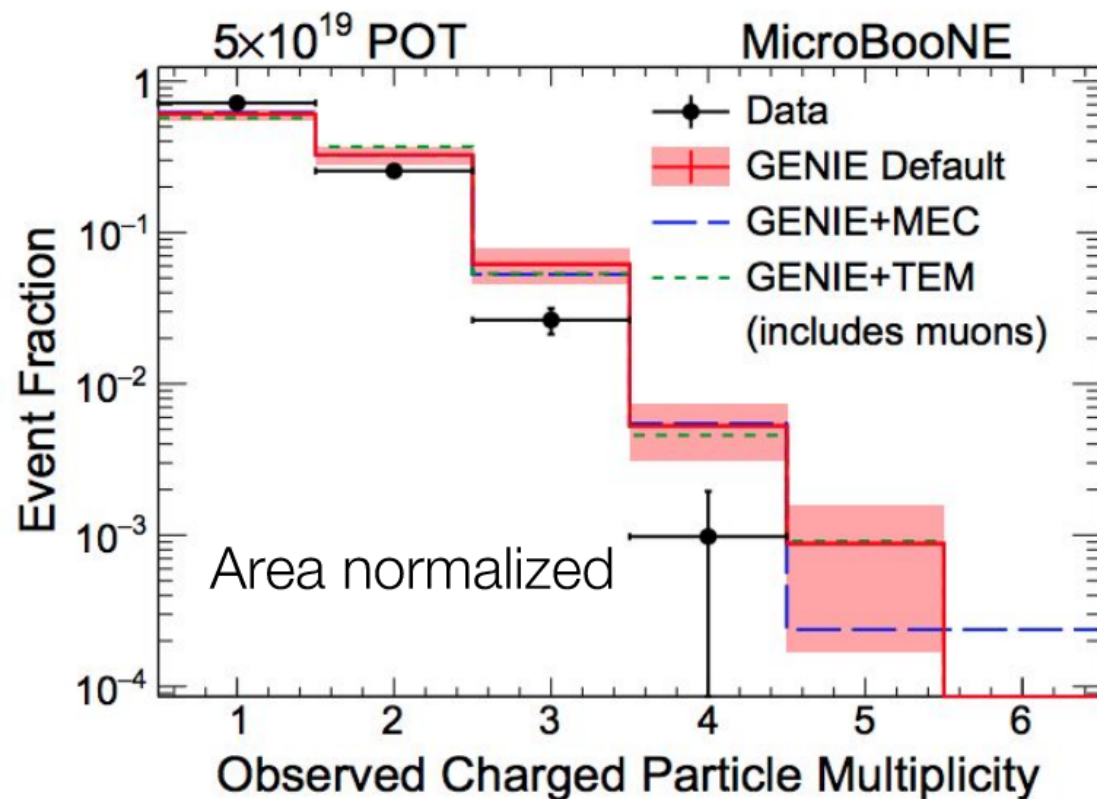
All are cut-based selections addressing similar challenges:

- Cosmic mitigation
- Vertex identification
- Containment



# Charged Particle Multiplicity

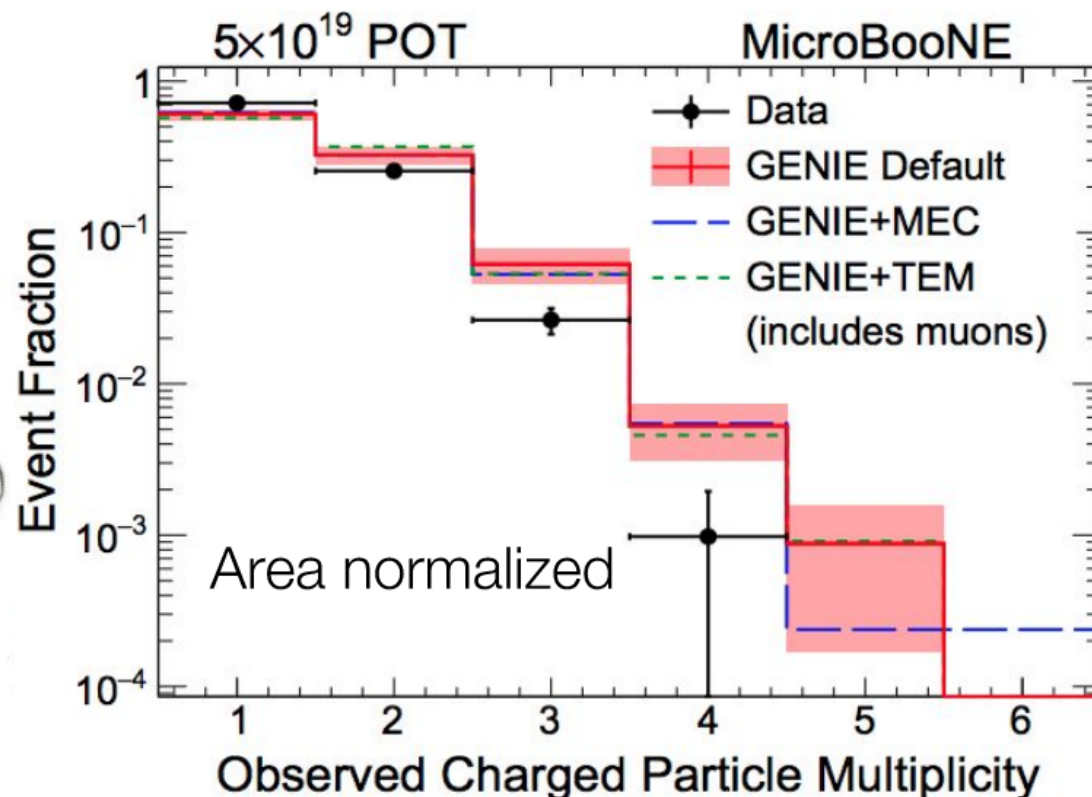
- MicroBooNE's first published physics result!
- The number of charged particles ejected from a neutrino interaction provides a powerful probe of nuclear models.  
⇒ an important measurement for improving neutrino generators



“Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions”, [arXiv:1805.06887](https://arxiv.org/abs/1805.06887), submitted to PRD (2018)

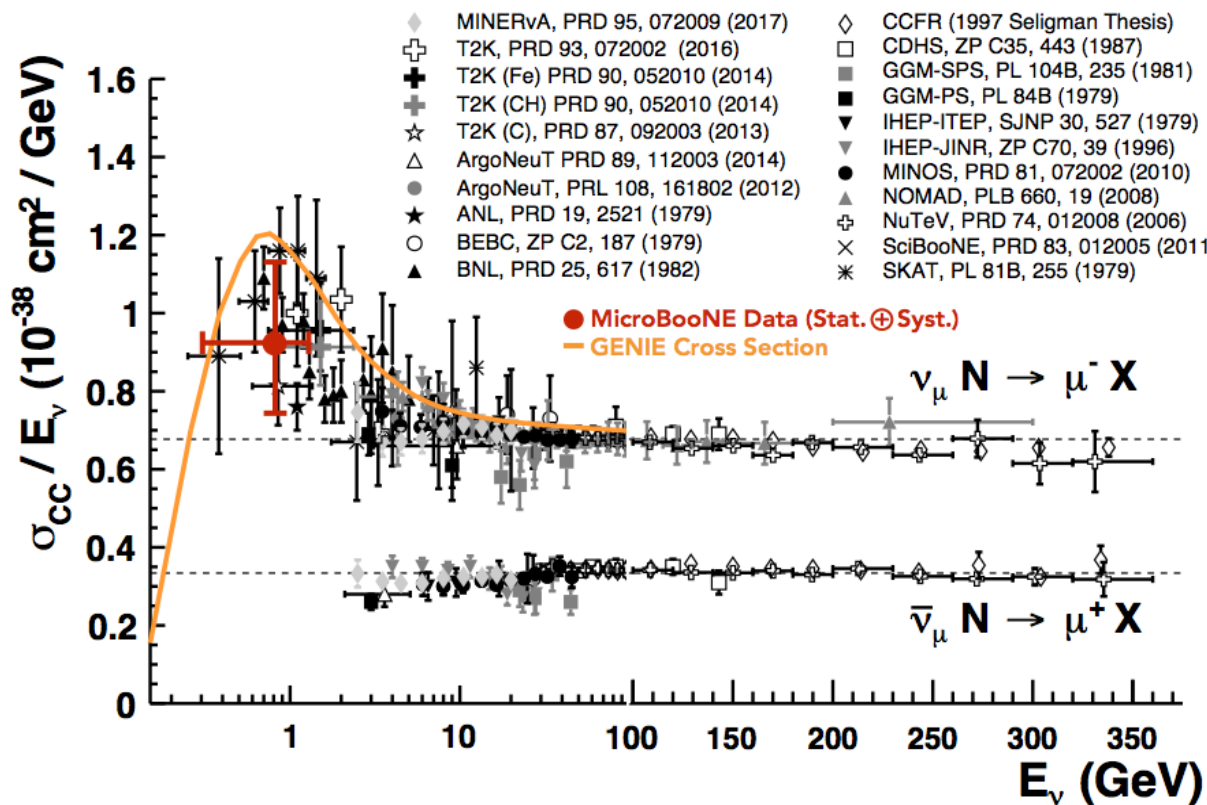
# Charged Particle Multiplicity

- Results consistent with GENIE models (default, MEC, TEM) within  $2\sigma$  – require more statistics for stronger model discrimination.
- Results favour lower multiplicities.



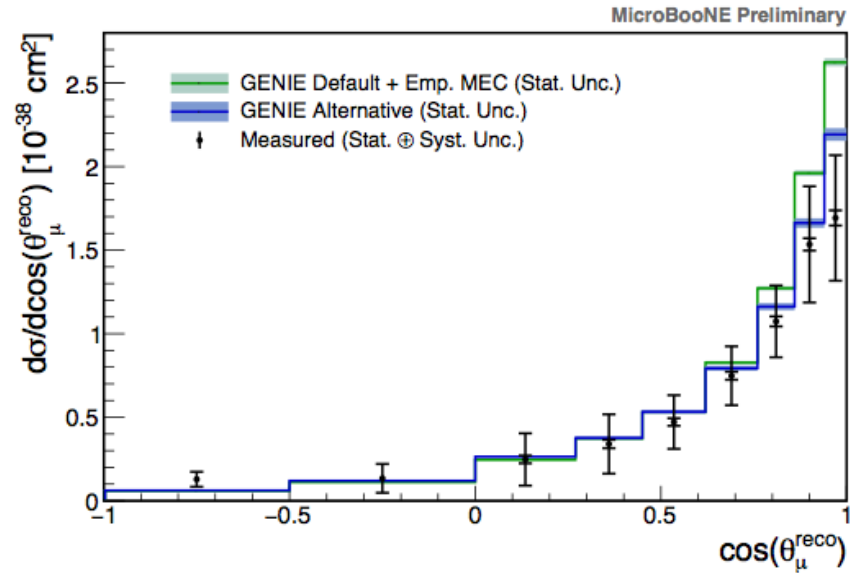
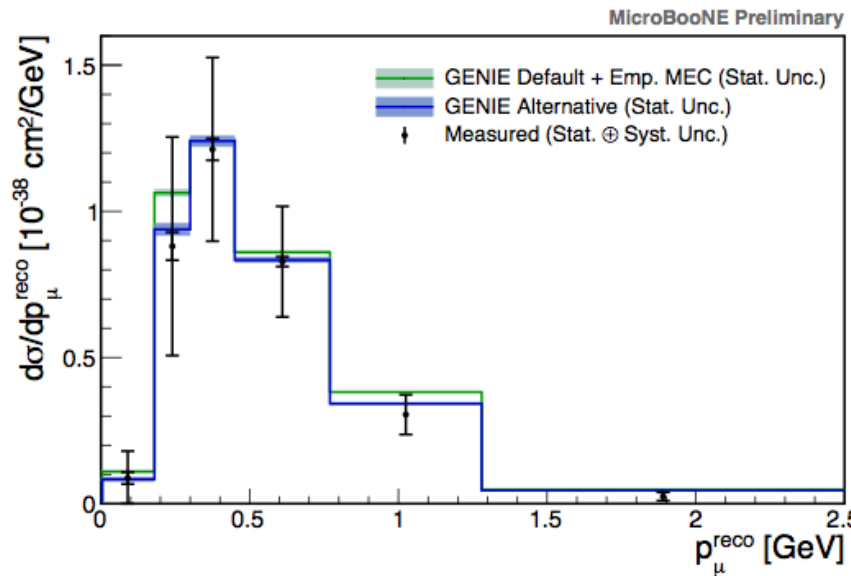
“Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions”, [arXiv:1805.06887](https://arxiv.org/abs/1805.06887), submitted to PRD (2018)

# $\nu_\mu$ CC-Inclusive Cross-Section

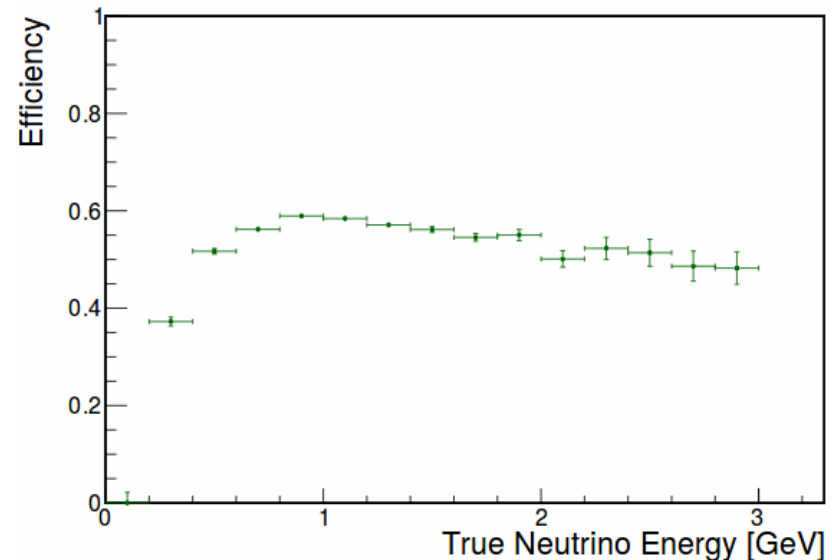


- First and simplest cross-section channel to measure.
- Provides benchmark to other experiments
- Direct bearing on DUNE oscillation signal.

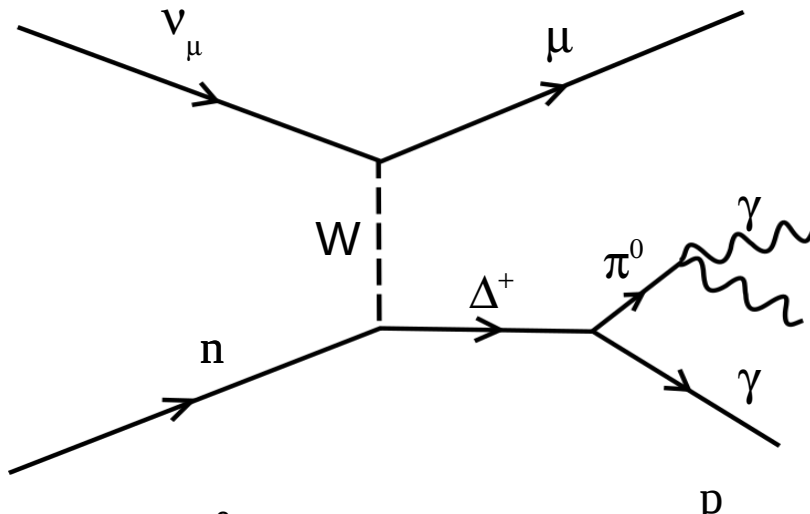
# $\nu_{\mu}$ CC-Inclusive Cross-Section



- Selection detailed in public note MICROBOONE-NOTE-1045-PUB, 2018
- Double differential cross-section coming soon!



# CC- $\pi^0$ Cross-Section

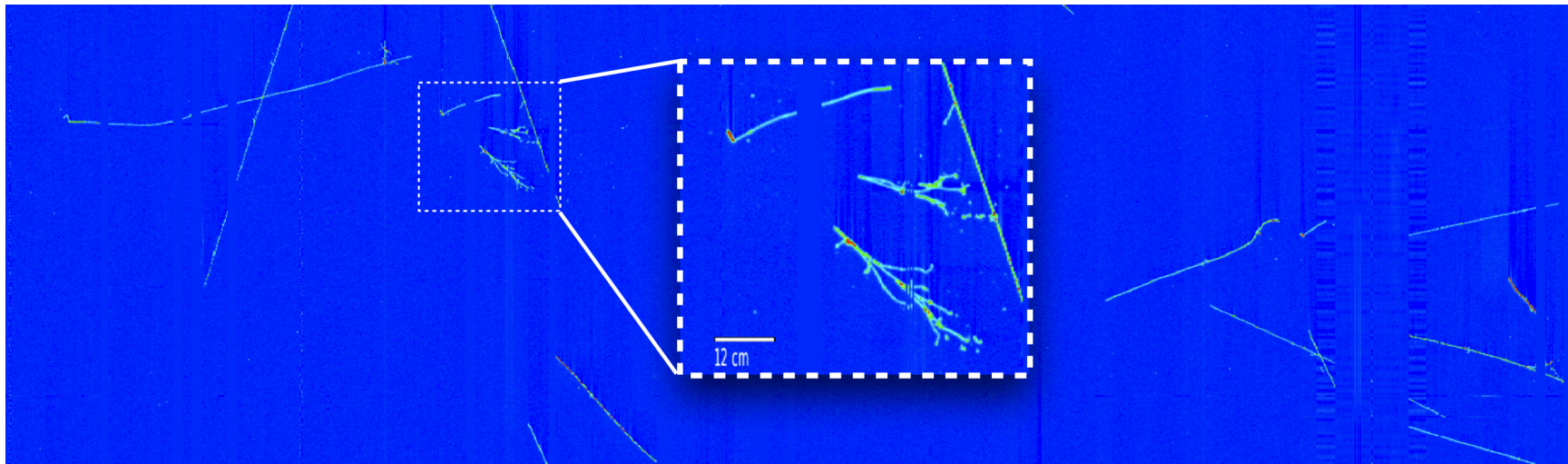


The CC- $\pi^0$  neutrino interaction channel

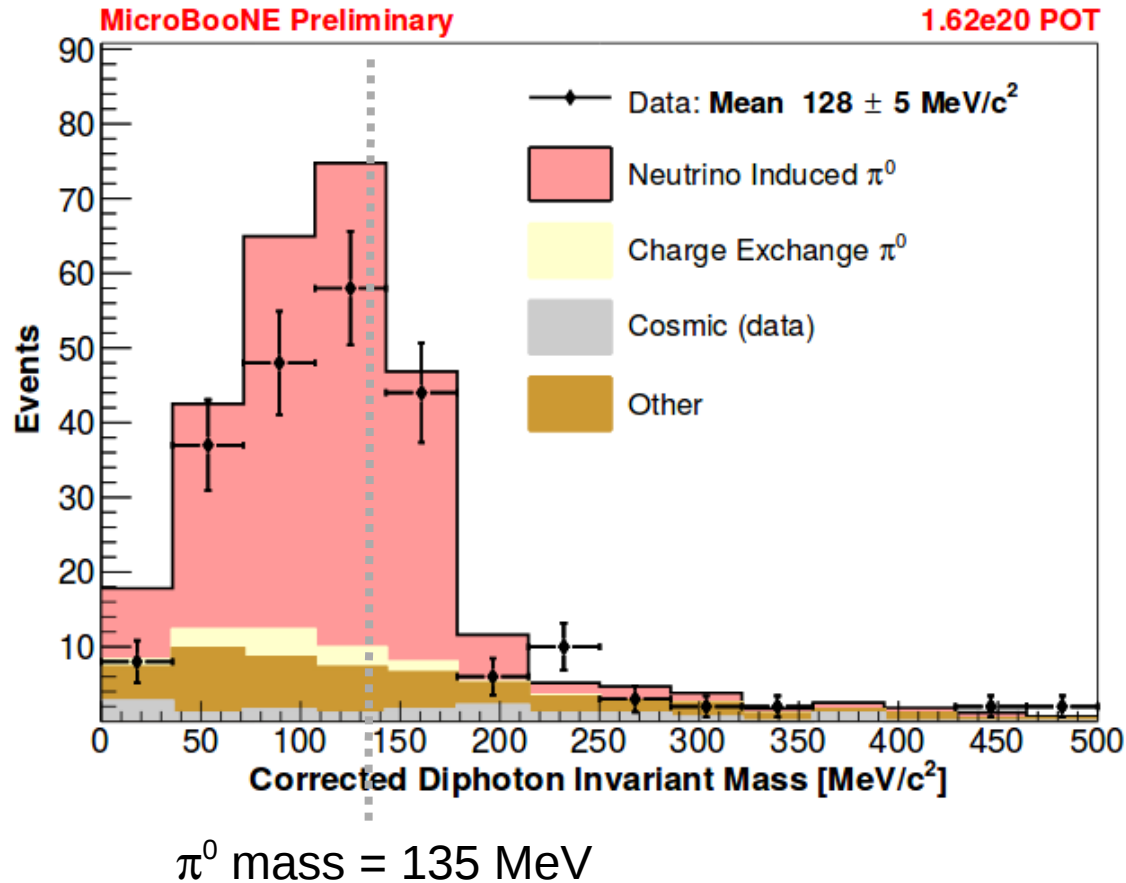
$\pi^0$  production is a critical background for low-energy excess searches: produces EM showers similar to  $\nu_e$  appearance signal.

$\Rightarrow$  this measurement is a good test of our shower reconstruction.

MicroBooNE has measured the first CC- $\pi^0$  cross-section on Ar.



# CC- $\pi^0$ Cross-Section



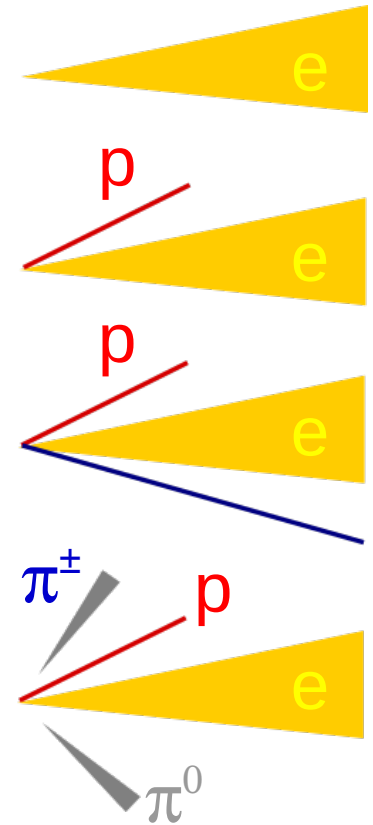
- Selected events correctly reproduce expected  $\pi^0$  invariant mass.
- Selection described in public note MICROBOONE-NOTE-1032-PUB, 2018

$$\left\langle \sigma^{\nu\mu\text{CC}\pi^0} \right\rangle_{\Phi} = (1.94 \pm 0.16 [\text{stat.}] \pm 0.60 [\text{syst.}]) \times 10^{-38} \frac{\text{cm}^2}{\text{Ar}}$$

# Progress Towards $\nu_e$ Appearance

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- Multiple complementary analyses.
- Blind search developing analyses on 4% of collected BNB data.
- Cross-check against large sample of open NuMI data.
  - Higher  $\nu$  energy
  - Off-axis
- We want to perform our cross-section measurements first to ensure we have a good understanding of our signal and background channels.



The  $\nu_e$  appearance signal comes in many forms

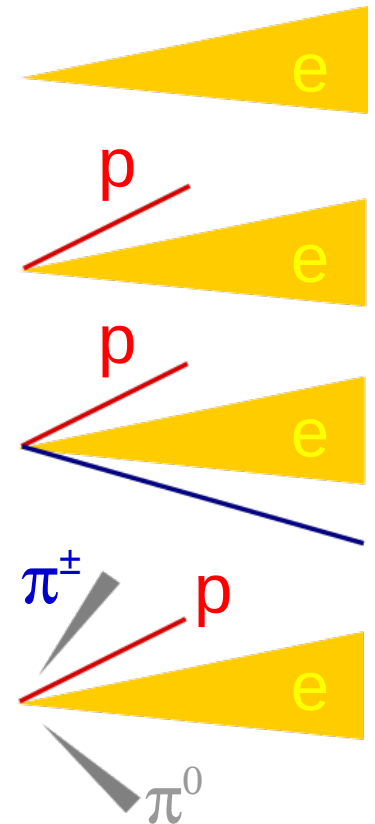
# Progress Towards $\nu_e$ Appearance

- Multiple complementary analyses.

$\nu_e$ analyses	Single photon analyses
<ul style="list-style-type: none"><li>• 1e1p (Deep Learning)</li><li>• 1eNp (Pandora)</li><li>• 1e inclusive (Pandora, WireCell)</li></ul>	<ul style="list-style-type: none"><li>• <math>1\gamma 0p</math> (Pandora)</li><li>• <math>1\gamma 1p</math> (Pandora)</li></ul>

## Recent Public Notes:

- R. Soleti, Electron-neutrino reconstruction in MicroBooNE using the Pandora pattern reconstruction, MICROBOONE-NOTE-1038-PUB, 2018
- R. Murrells, Search for NC single photon events in MicroBooNE, MICROBOONE-NOTE-1041-PUB, 2018
- M. Ross-Lonergan, MicroBooNE tests of the MiniBooNE low-energy excess, MICROBOONE-NOTE-1043-PUB, 2018

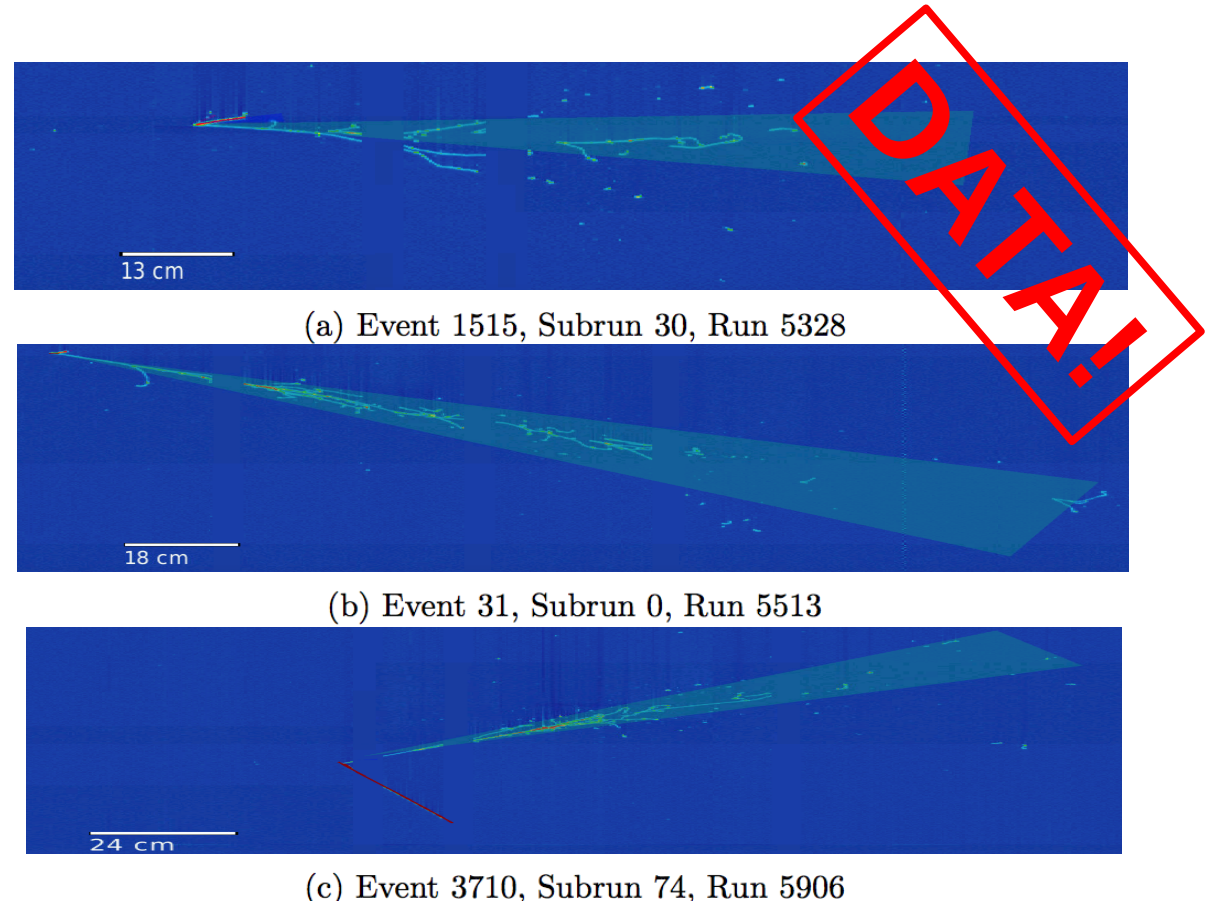


The  $\nu_e$  appearance signal comes in many forms

# Progress Towards $\nu_e$ Appearance

Example events selected by the 1eNp analysis show good reconstruction of EM showers.

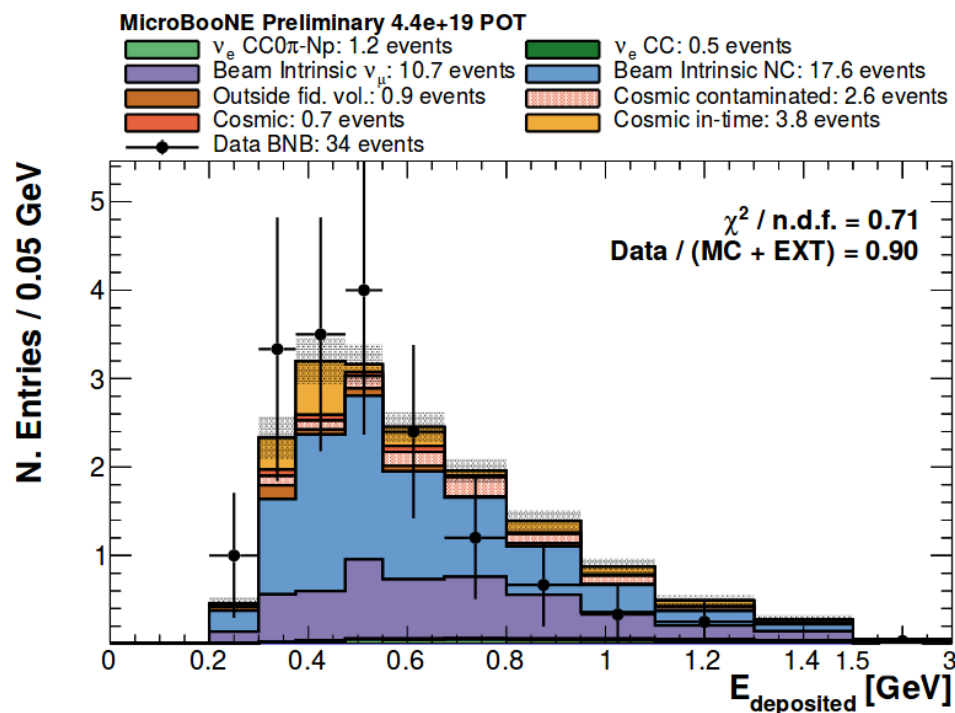
See public note  
(MICROBOONE-  
NOTE-1038-PUB)



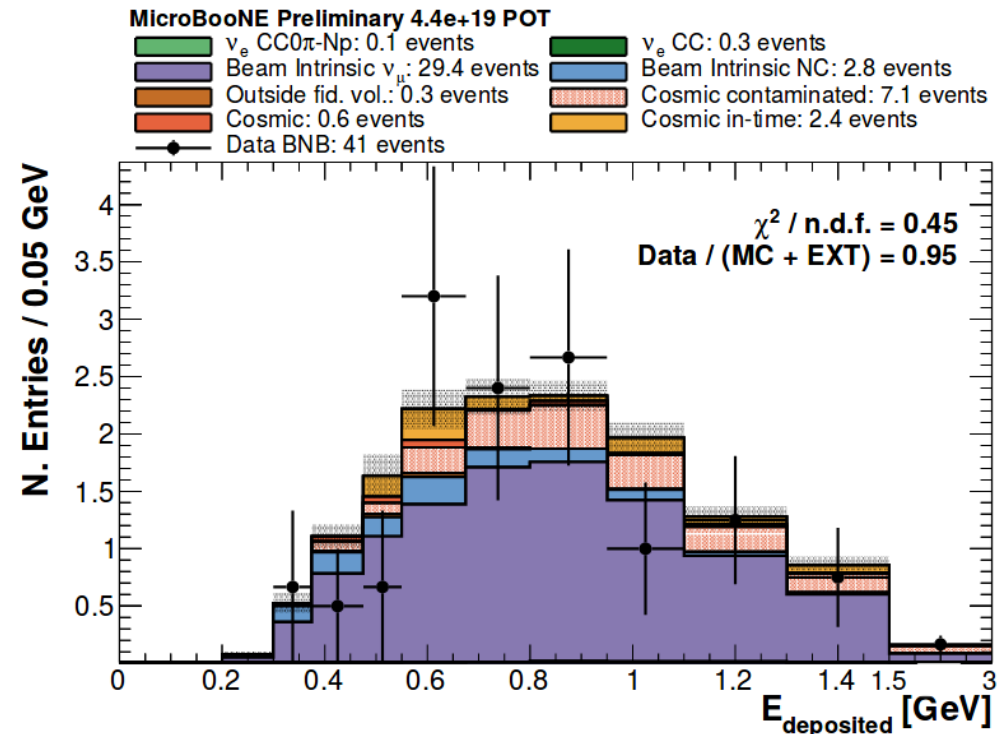
3 selected  $\nu_e$  candidate events

# Progress Towards $\nu_e$ Appearance

Sideband checks show good data-MC agreement:



Photon-enhanced



CC $\nu_\mu$ -enhanced

# Progress Towards $\nu_e$ Appearance

Analyses so far have shown us where we need to improve:

- **Cosmic removal:** we are improving our cosmic removal algorithms while simultaneously integrating a new cosmic ray tagger system to the detector itself.
- **Particle identification:** more robust & sophisticated PID methods are being implemented.
- **Reconstruction efficiency:** effort is being focused on improving reconstruction efficiency at low energies.
- **Machine learning:** these techniques have shown great promise and are being developed further.

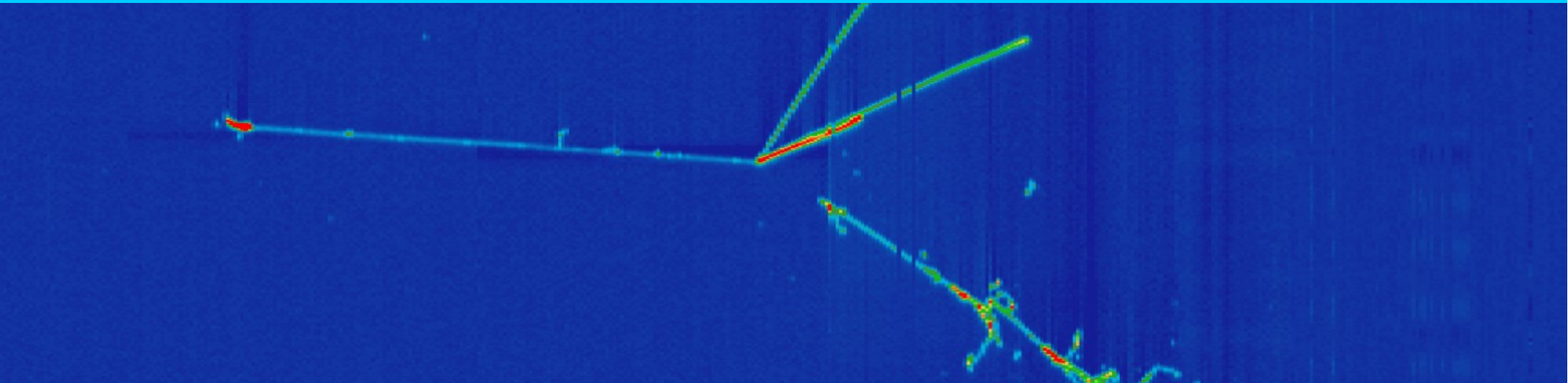
We aim to perform an end-to-end analysis with these improvements, validated on the NuMI sample, before publication.

# Conclusions

- MicroBooNE is providing valuable  $\nu$ -Ar interaction data for the SBN programme and other LArTPC detectors (e.g. DUNE).
  - First cross-section results are out:
    - $\nu_\mu$  CC inclusive
    - $\text{CC}\pi^0$
    - Charged particle multiplicity
  - Many more underway.
- Automated LArTPC event reconstruction has been demonstrated on MicroBooNE data and is growing more sophisticated.
- We have performed our first fully automated  $\nu_e$ /single  $\gamma$  selections, and are making improvements towards a complete low-energy excess analysis.
- Much of our work is documented on a rapid timescale on our public notes page: <http://microboone.fnal.gov/public-notes/>

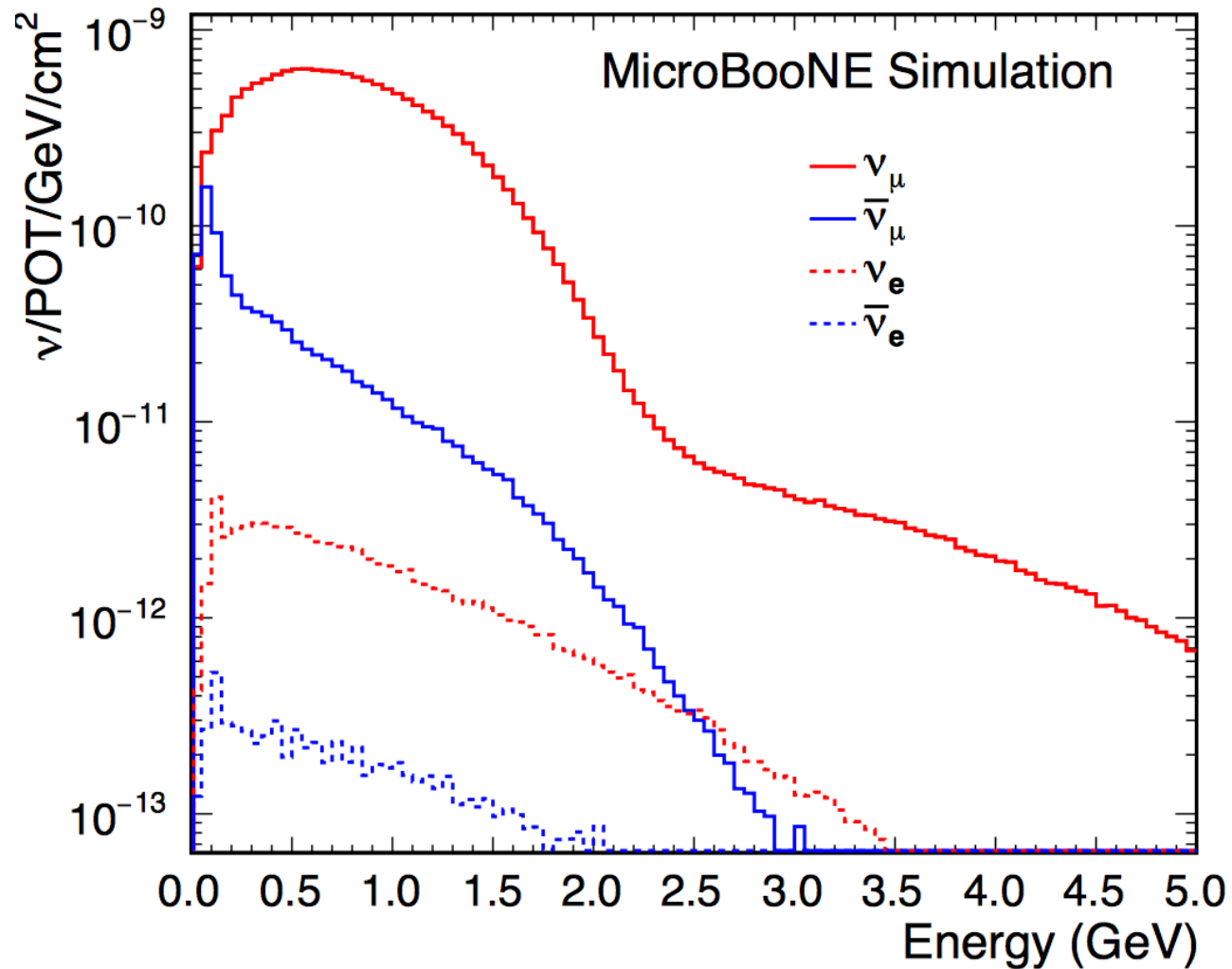


Thank You!

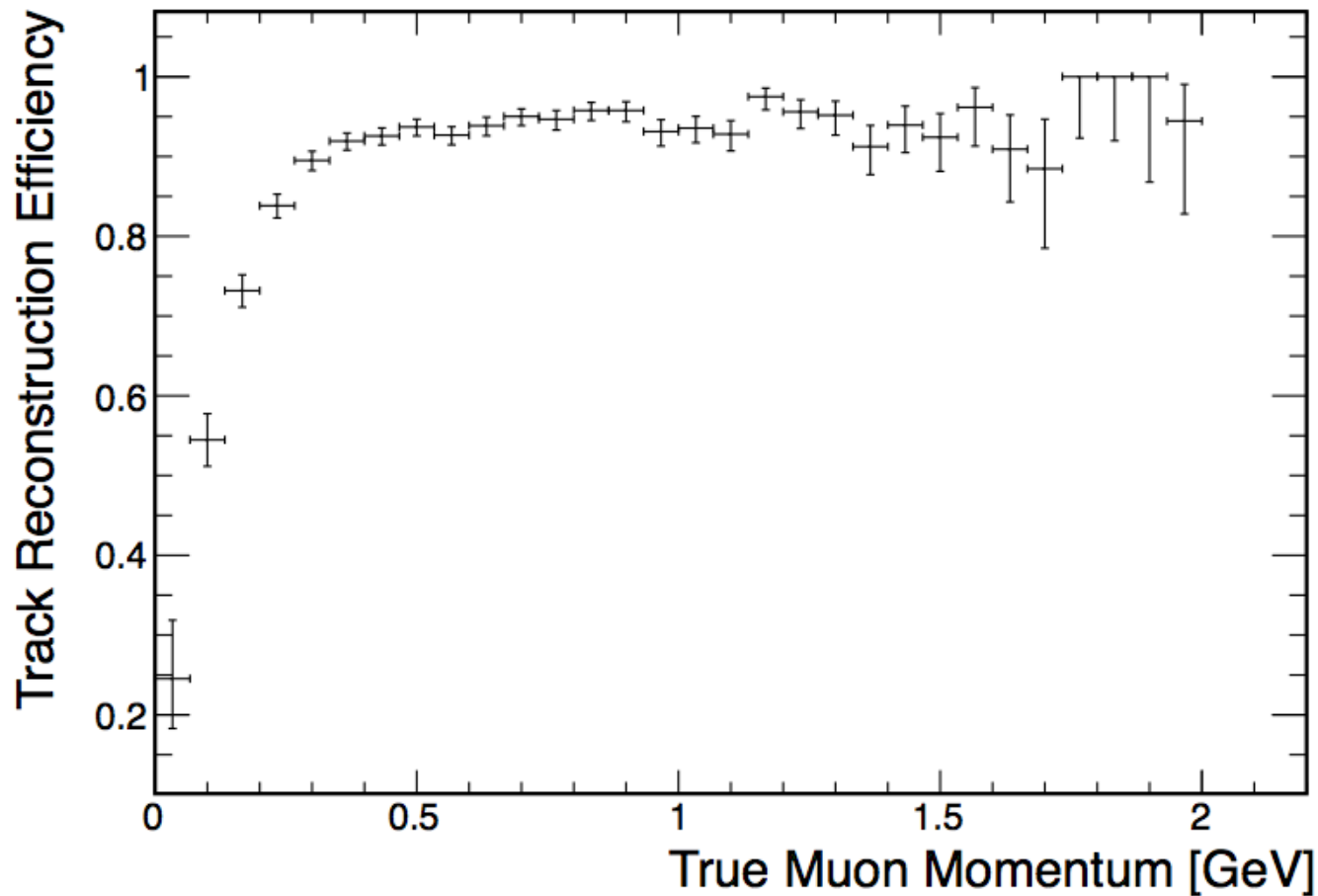


# Backups

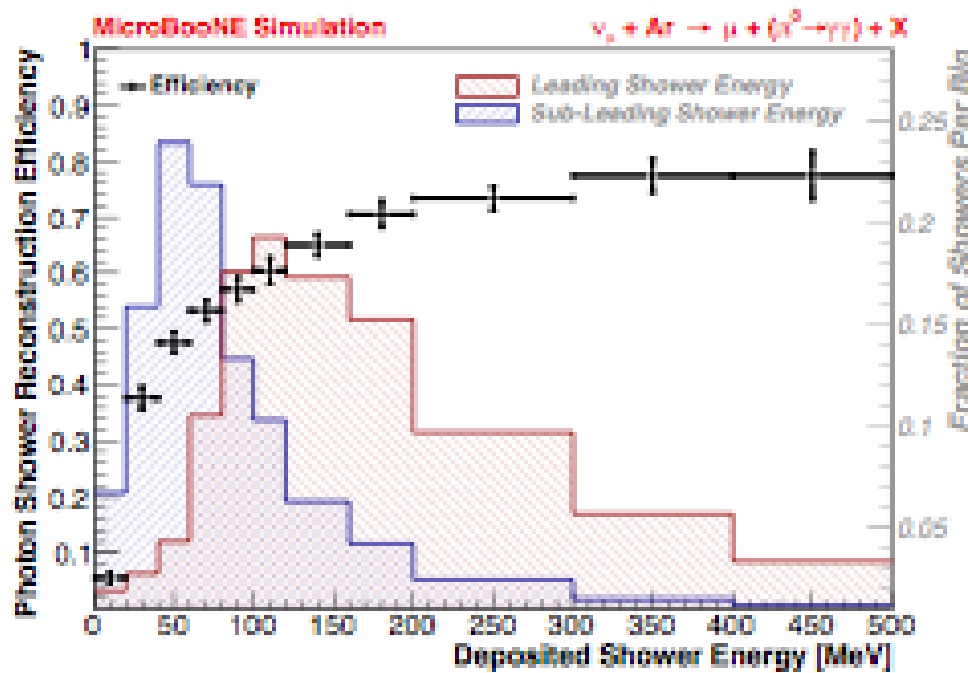
# BNB Flux



# CC-Inclusive Track Reconstruction Efficiency



# CC- $\pi^0$ Shower Reconstruction Efficiency



## Reconstruction efficiencies:

- 62% for leading CC- $\pi^0$  shower
- 50% for subleading CC- $\pi^0$  shower
- 80% above 300 MeV

## Selection efficiencies:

- 1 shower: 771 events  
Efficiency 17%, purity 53%
- 2 showers: 224 events  
Efficiency 6%, purity 64%

# Physics Results

## PUBLICATIONS

- “Comparison of Muon-Neutrino-Argon Multiplicity Distributions Observed by MicroBooNE to GENIE Model Predictions”, [arXiv:1805.06887](https://arxiv.org/abs/1805.06887), submitted to PRD

## PUBLIC NOTES

- “First measurement of muon neutrino charged-current neutral pion production in LArTPC”, MICROBOONE-NOTE-1032-PUB, 2018
- “First measurement of muon neutrino charged-current inclusive cross-section measurement in MicroBooNE”, MICROBOONE-NOTE-1045-PUB, 2018
- “Towards measurements of nuclear effects in MicroBooNE”, MICROBOONE-NOTE-1046-PUB, 2018
- “Electron-neutrino reconstruction in MicroBooNE using the Pandora pattern reconstruction”, MICROBOONE-NOTE-1038-PUB, 2018
- “Search for NC single photon events in MicroBooNE”, MICROBOONE-NOTE-1041-PUB, 2018
- “MicroBooNE tests of the MiniBooNE low-energy excess”, MICROBOONE-NOTE-1043-PUB, 2018
- “Booster Neutrino Flux Prediction at MicroBooNE”, MICROBOONE-NOTE-1031-PUB, 2018

# Detector Physics Results

## PUBLICATIONS

- “Ionization Electron Signal Processing in Single Phase LAr TPCs II: Data/Simulation Comparison and Performance in MicroBooNE”, [arXiv:1804.02583](https://arxiv.org/abs/1804.02583), submitted to JINST
- “Ionization Electron Signal Processing in Single Phase LAr TPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation”, [arXiv:1802.08709](https://arxiv.org/abs/1802.08709), accepted by JINST
- “Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC”, [arXiv:1705.07341](https://arxiv.org/abs/1705.07341), [JINST 12, P08003 \(2017\)](https://arxiv.org/abs/1705.07341)

## PUBLIC NOTES

- “A Measurement of the Attenuation of Drifting Electrons in the MicroBooNE LArTPC”, MICROBOONE-NOTE-1026-PUB, (2017)
- “Establishing a Pure Sample of Side-Piercing Through-Going Cosmic-Ray Muons for LArTPC Calibration in MicroBooNE”, MICROBOONE-NOTE-1028-PUB, (2017)
- “Study of Space Charge Effects in MicroBooNE”, MICROBOONE-NOTE-1018-PUB, (2016)
- “A Method to Extract the Charge Distribution Arriving at the TPC Wire Planes in MicroBooNE”, MICROBOONE-NOTE-1017-PUB, (2016)
- “MicroBooNE Detector Stability”, MICROBOONE-NOTE-1013-PUB, (2016)
- “Measurement of the Electronegative Contaminants and Drift Electron Lifetime in the MicroBooNE Experiment”, MICROBOONE-NOTE-1003-PUB, (2016)
- “Noise Dependence on Temperature and LAr Fill Level in the MicroBooNE Time Projection Chamber”, MICROBOONE-NOTE-1001-TECH, (2016)

# Reconstruction and Calibration Results

## PUBLICATIONS

- “Measurement of Cosmic Ray Reconstruction Efficiencies in the MicroBooNE LAr TPC Using a Small External Cosmic Ray Counter”, [arXiv:1707.09903](#), [JINST 12, P12030 \(2017\)](#)
- “Michel Electron Reconstruction Using Cosmic Ray Data from the MicroBooNE LAr TPC”, [arXiv:1704.02927](#), [JINST 12, P09014 \(2017\)](#)
- “Determination of Muon Momentum in the MicroBooNE LAr TPC Using an Improved Model of Multiple Coulomb Scattering”, [arXiv:1703.06187](#), [JINST 12 P10010 \(2017\)](#)

## PUBLIC NOTES

- “Vertex finding and reconstruction for contained two-track events in the MicroBooNE detector”, MICROBOONE-NOTE-1042-PUB, 2018
- “Towards automated neutrino selection at MicroBooNE using tomographic event reconstruction”, MICROBOONE-NOTE-1040-PUB, 2018
- Hunting muon neutrinos in microboone with deep learning techniques, MICROBOONE-NOTE-1051-PUB, 2018
- “Reconstruction Performance Studies with MicroBooNE Data in Support of Summer 2018 Analyses”, MICROBOONE-NOTE-1049-PUB, 2018
- “Detector Calibration using through going and stopping muons in the MicroBooNE LArTPC”, MICROBOONE-NOTE-1048-PUB, 2018
- Proton Track Identification in MicroBooNE Simulation for Neutral Current Elastic Events, MICROBOONE-NOTE-1025-PUB, 2017
- “A Comparison of Monte-Carlo Simulations and Data from MicroBooNE”, MICROBOONE-NOTE-1014-PUB, 2017
- “Demonstration of 3D Shower Reconstruction on MicroBooNE Data”, MICROBOONE-NOTE-1012-PUB, 2016