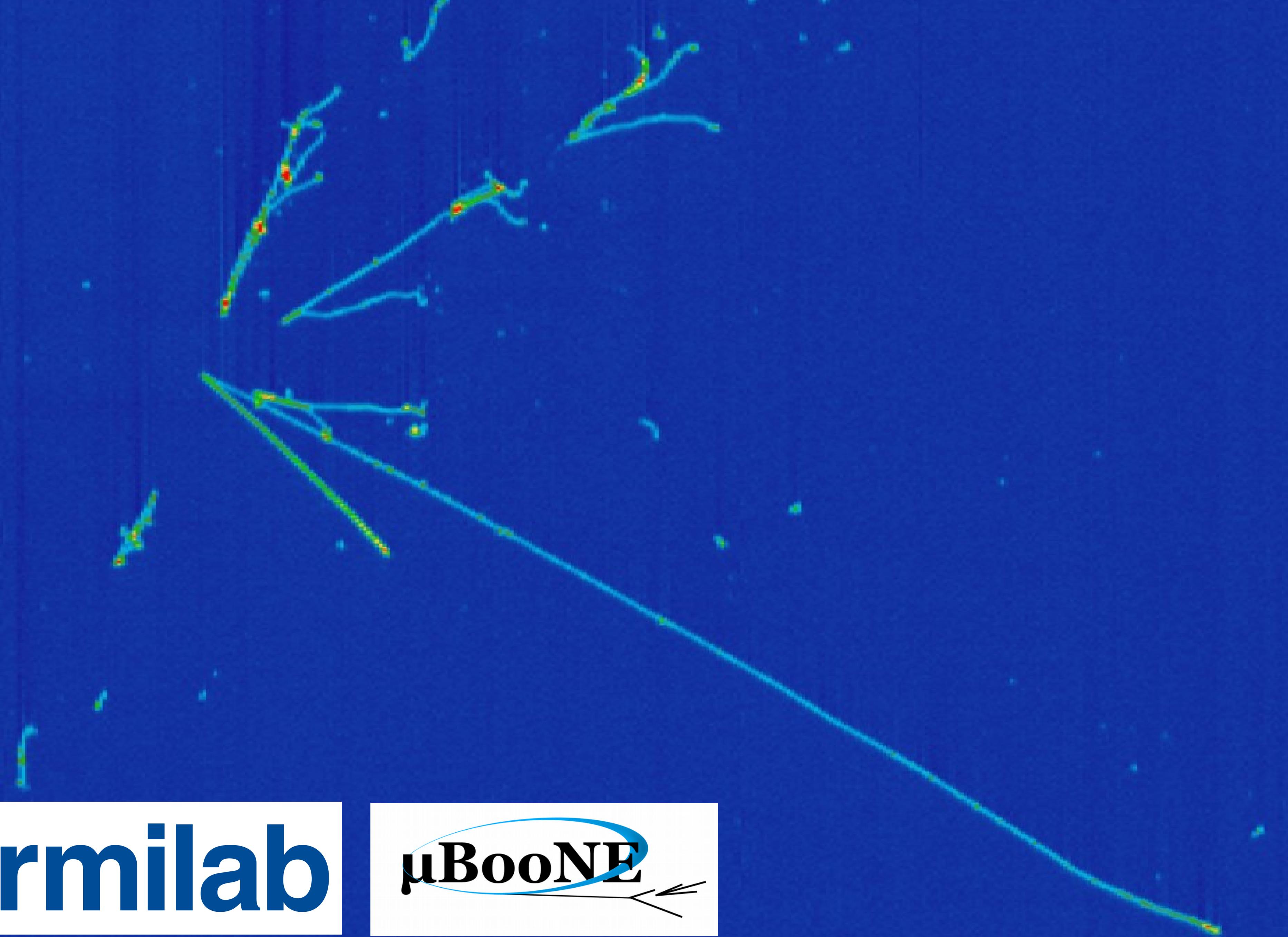
# The MicroBooNE Detector

July 5th 2018, ICHEP, Seoul, South Korea

**David Caratelli @ Fermilab**

**On behalf of the MicroBooNE Collaboration**

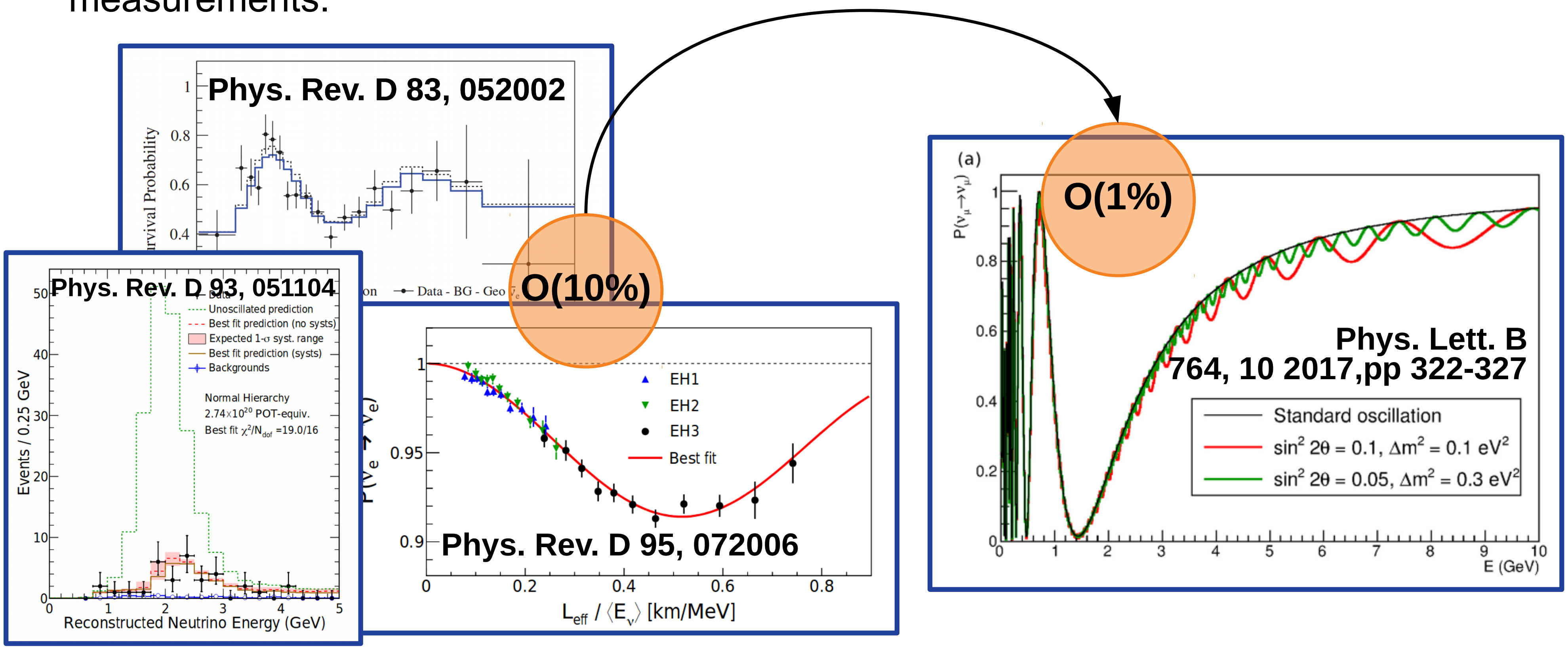


# Why build the MicroBooNE Detector?



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

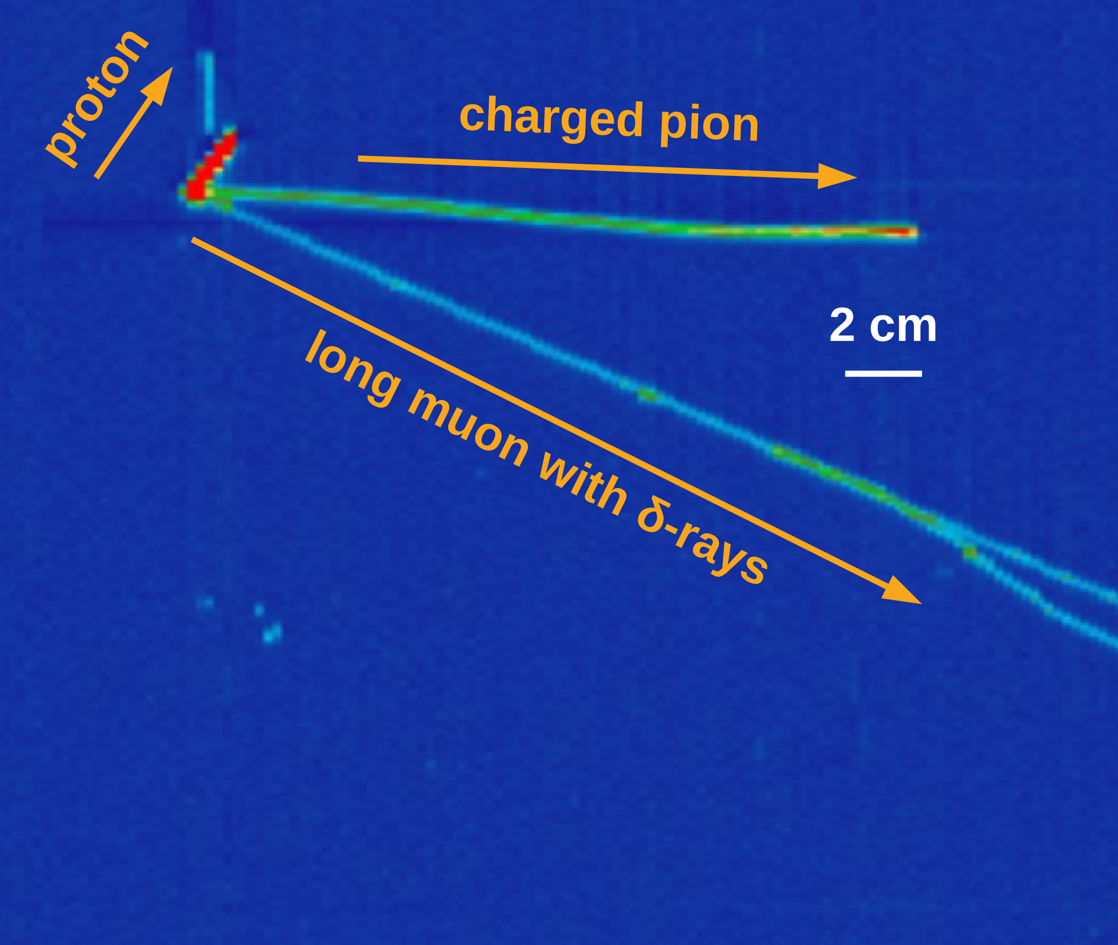
Achieving this program requires a new level of **precision** for accelerator-based neutrino measurements.

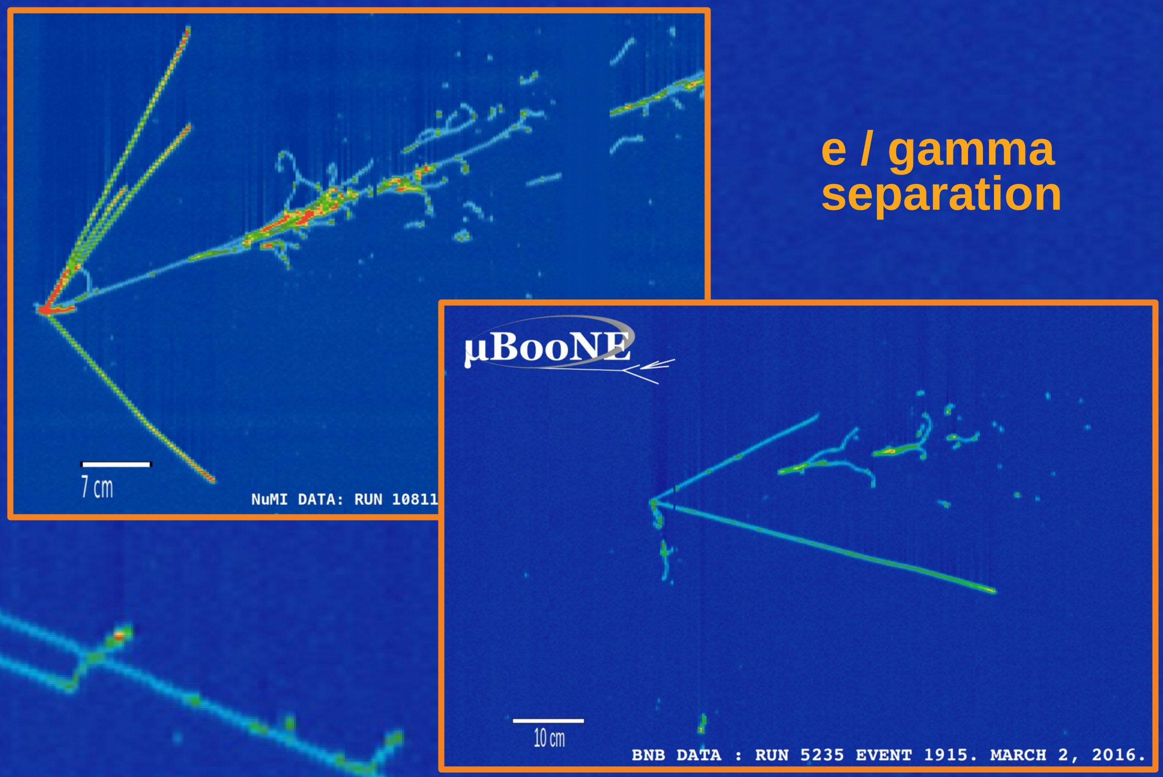



Neutrino **energy** determination is essential for these measurements.

MicroBooNE investigates sterile neutrinos @ Fermilab. **Detector needs** are the same for other SBN and DUNE programs.

# What we want from our detector




e / gamma separation

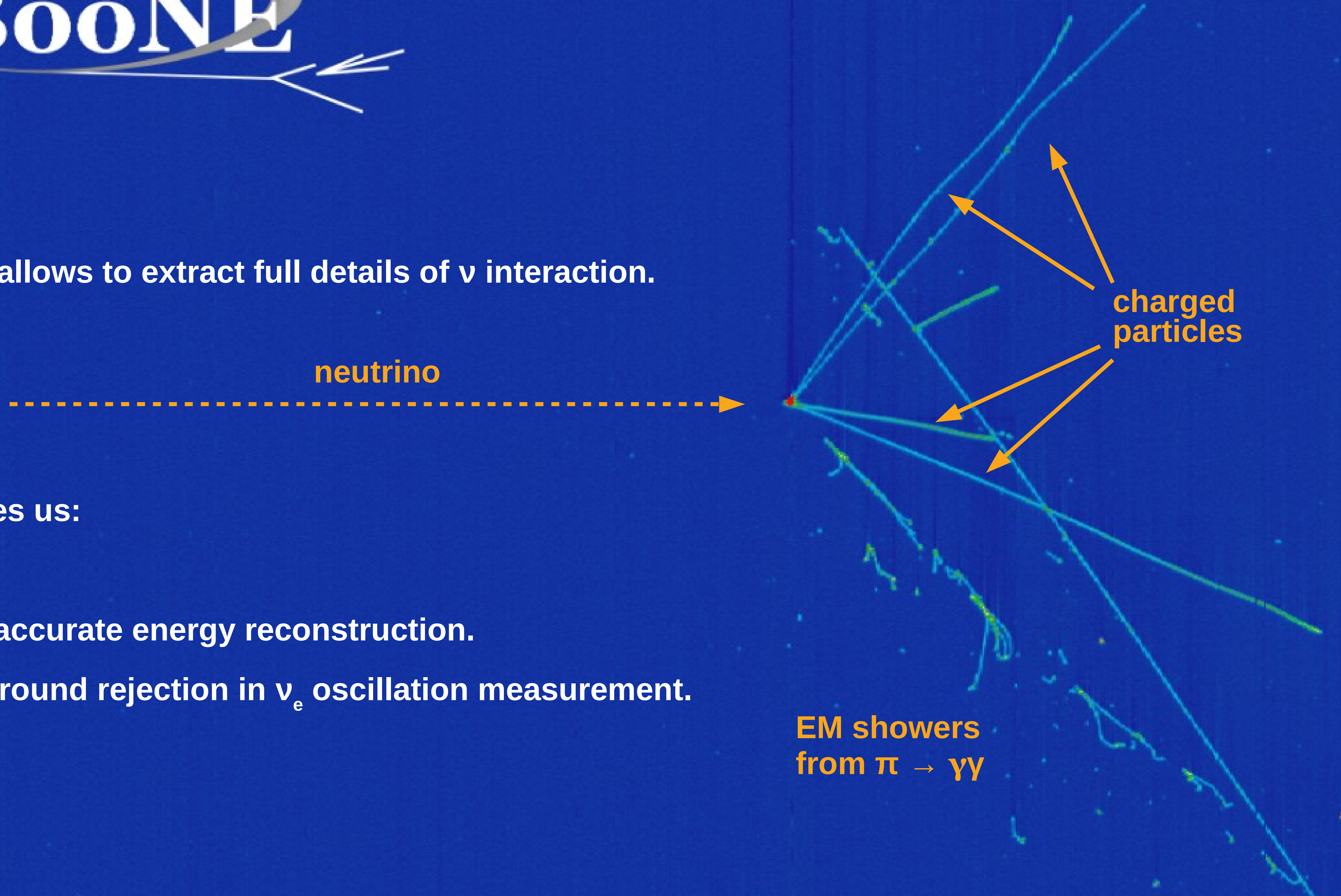
**We want to use our detector to accurately measure neutrino energies & flavor**

**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.**

# μBooNE

**LArTPC allows to extract full details of ν 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 reconstruciton, calibration, and analysis of large-scale LArTPC neutrino experiments.**

# The MicroBooNE Detector

David Caratelli, Fermilab : ICHEP 2018, Seoul, South Korea

# 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.

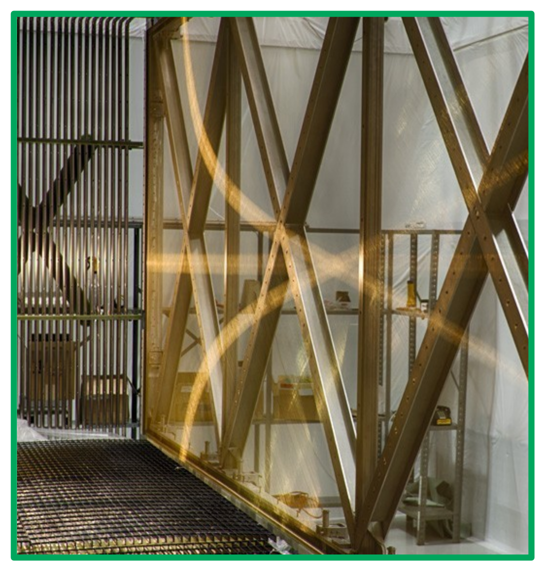
Surface detector → 5 kHz cosmic-ray rate.

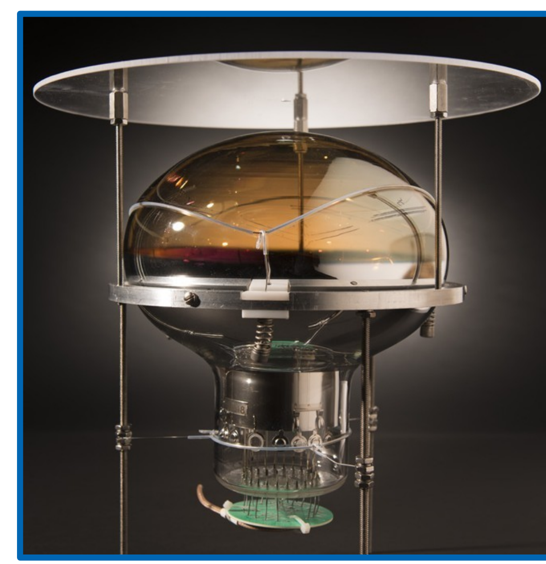
8k wires → mm spatial resolution.

70 kV → 2.3 ms drift-time.

32 PMTs for timing / background rejection.

Cosmic Ray Tagger installed in 2016/17

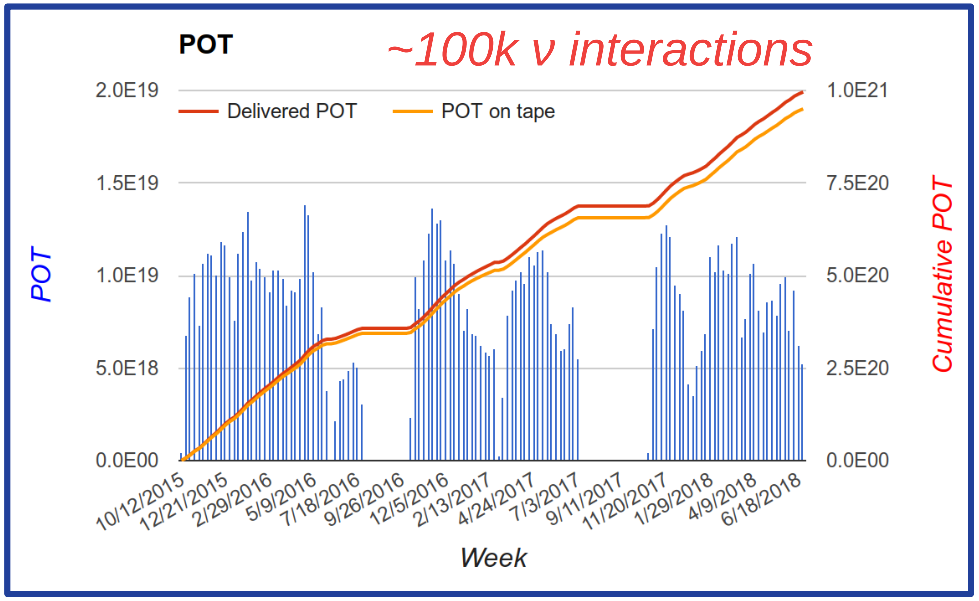





# MicroBooNE Operations

David Caratelli, Fermilab : ICHEP 2018, Seoul, South Korea

**MicroBooNE** studies **neutrino interactions** on the **Booster Neutrino Beamline** at Fermilab.
1 GeV $\nu_\mu \rightarrow$ 1 neutrino interaction per minute.

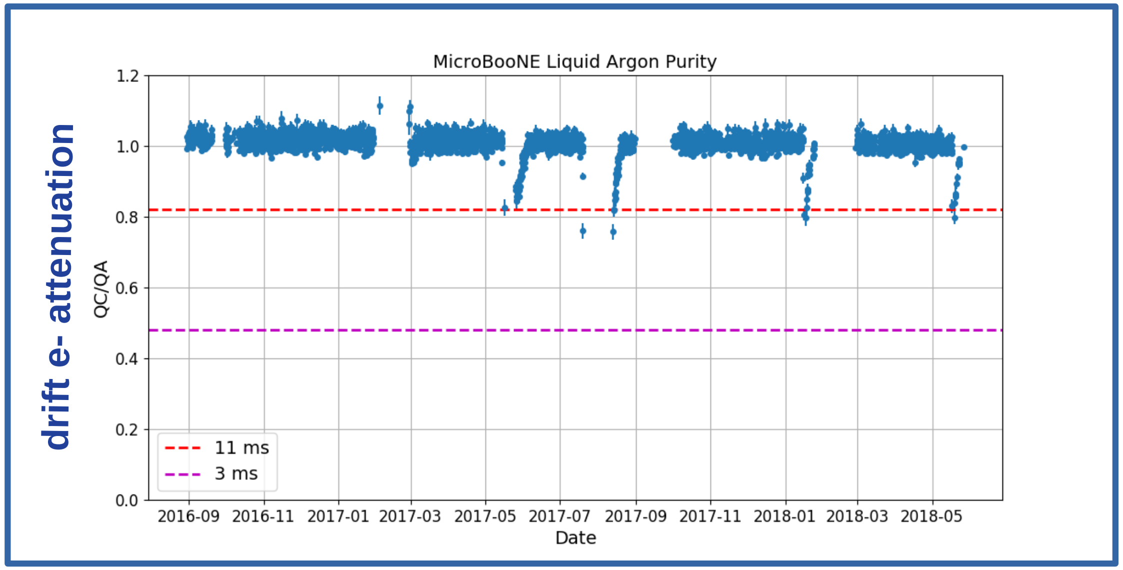



Data taking started in Fall 2015.

Three years of stable operations.

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

> 95% DAQ uptime.




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



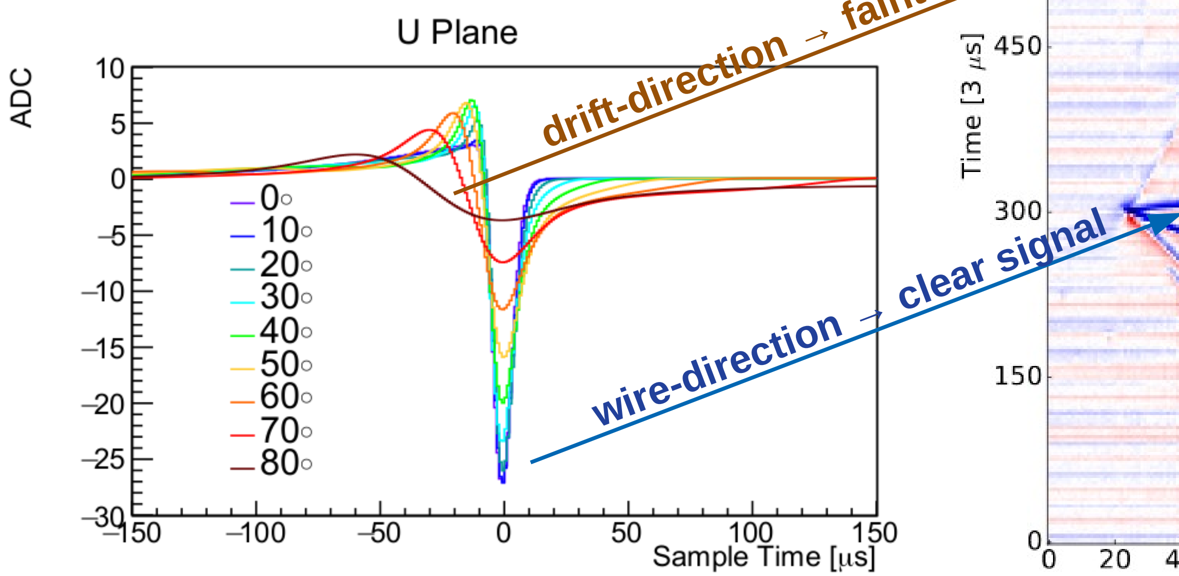
Extensive development of advanced techniques for noise-filtering and signal-processing.

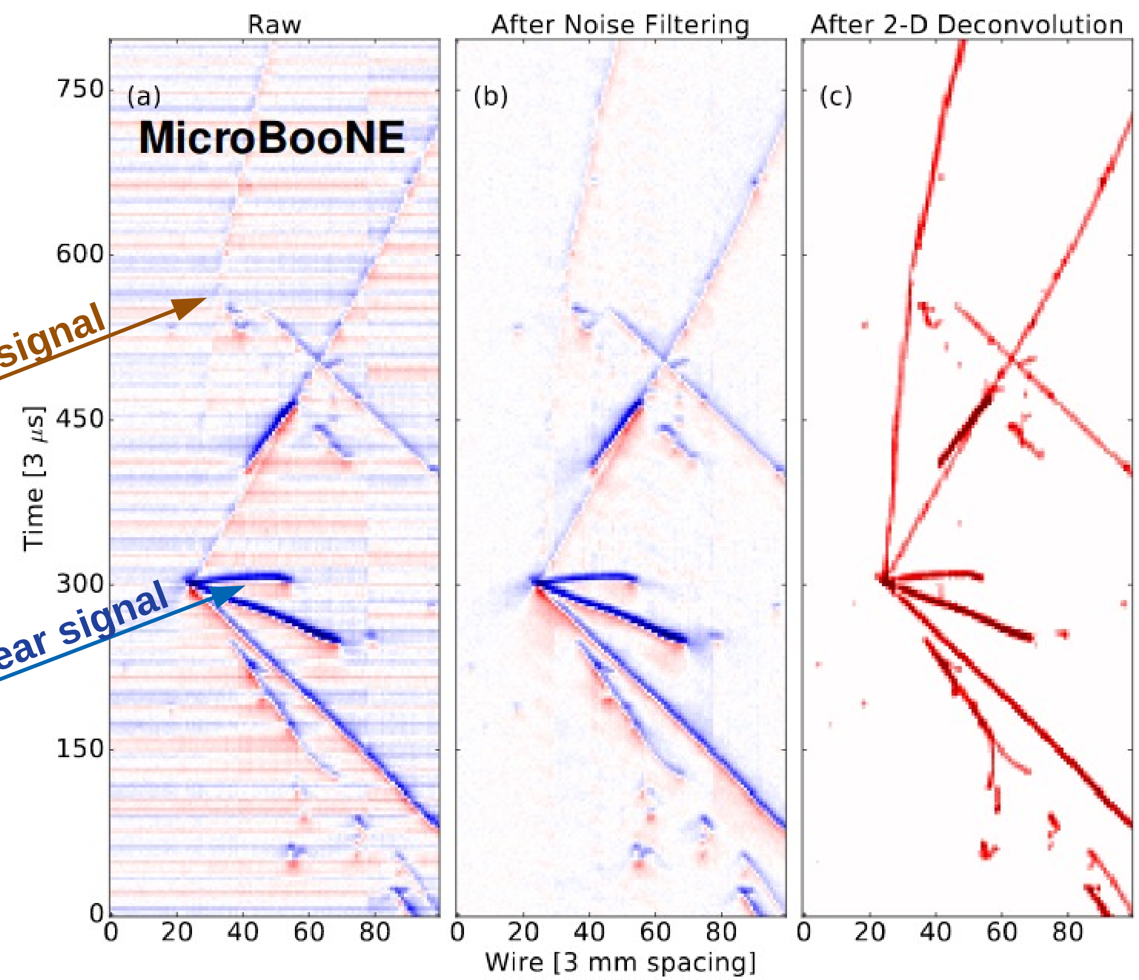
*Noise filtering*: JINST 12 P08003 (2017)

*Ionization and Signal Processing I & II*: arXiv:1804.02583, arXiv:1802.08709. (accepted by JINST)

Total absorption calorimeter with **anisotropic** response.

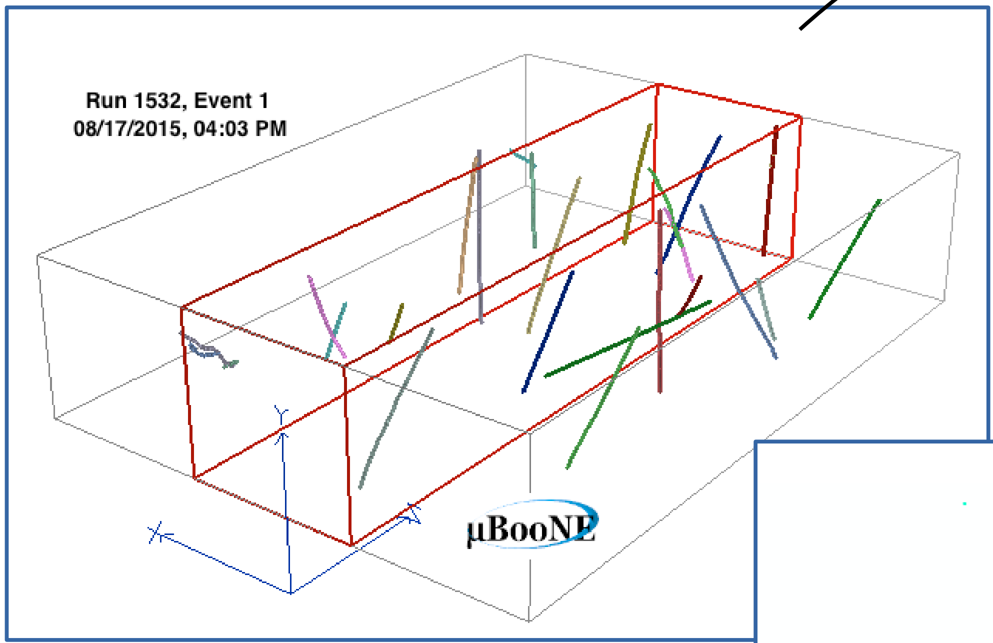
Different wire-planes and wire orientation causes significant variation in detector response.



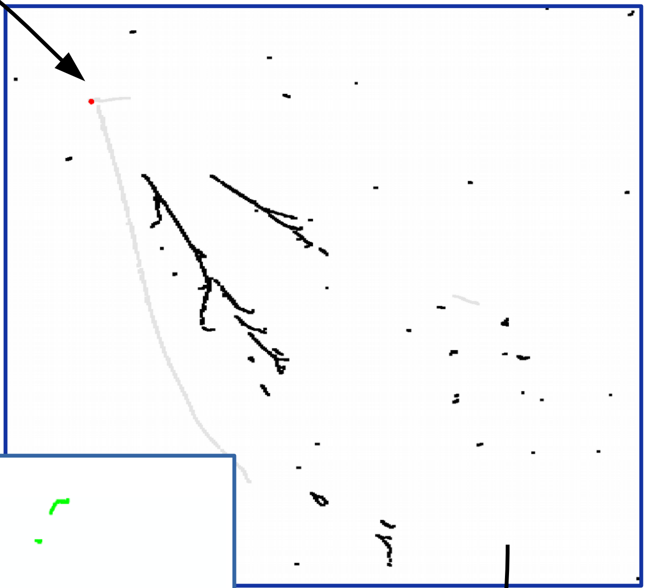
# High level pattern recognition

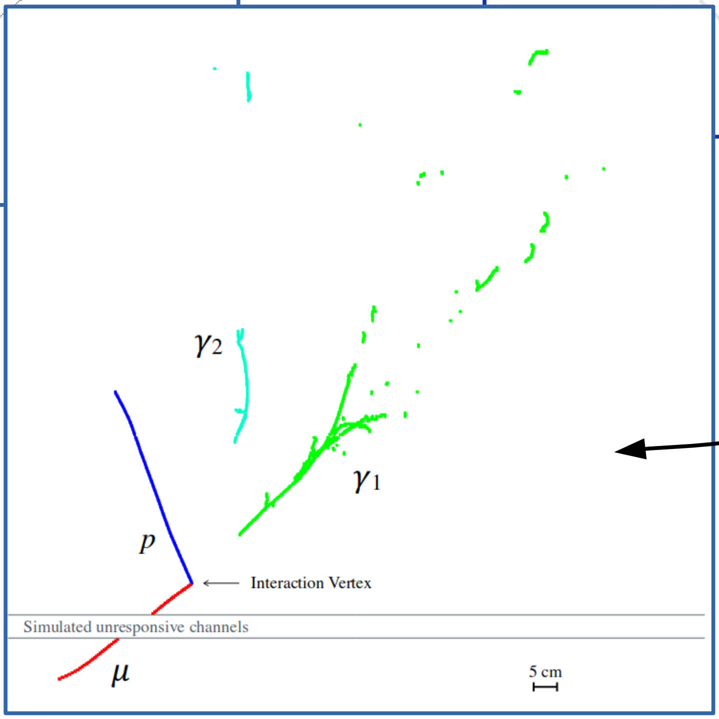
Multi-staged approach to perform high-quality pattern recognition.




1) event-slicing to isolate individual interactions

2) low-level pattern recognition






3) full interaction reconstruction

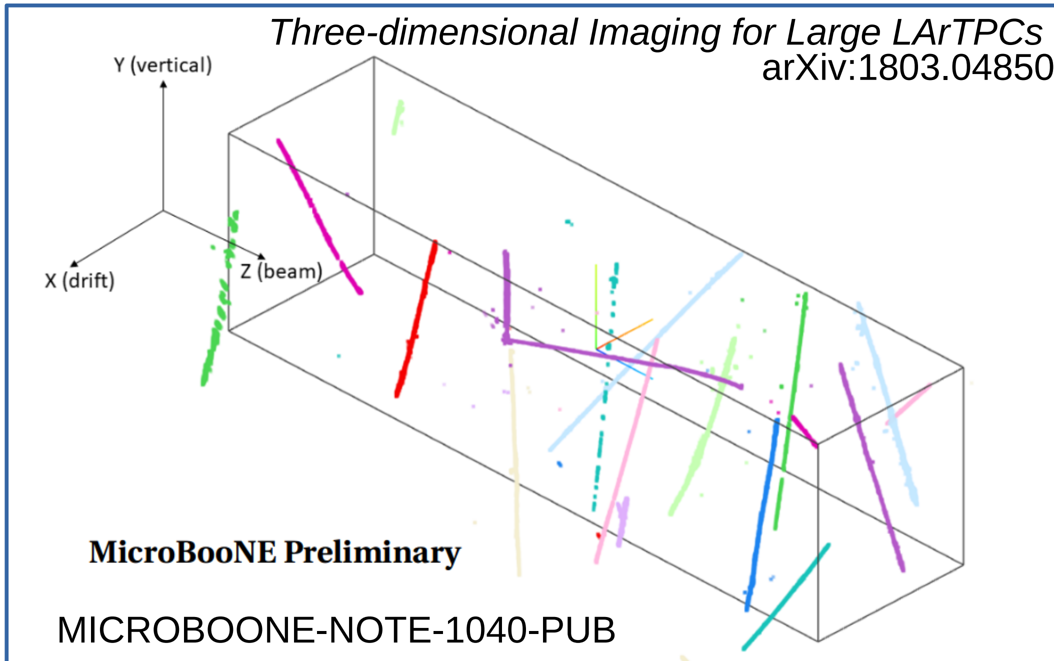
**Pandora multi-algorithm pattern-recognition**

**Eur. Phys. J. C78, 1, 82 (2018)**

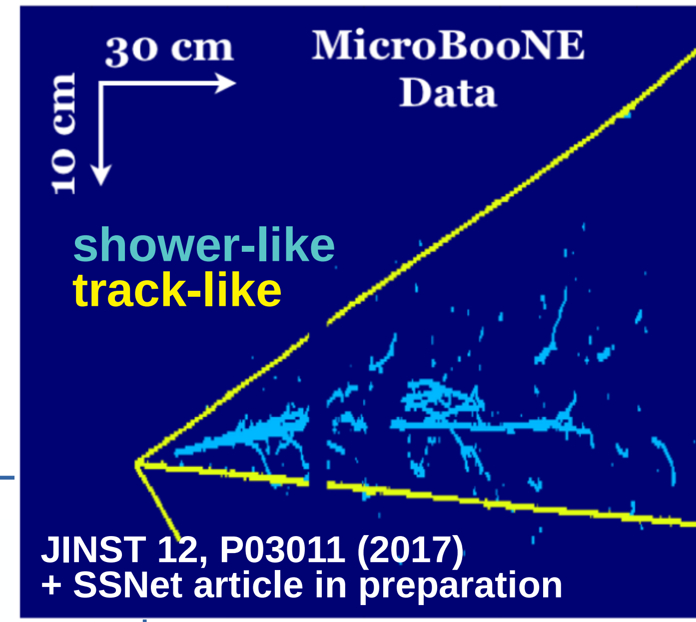
# High level pattern recognition

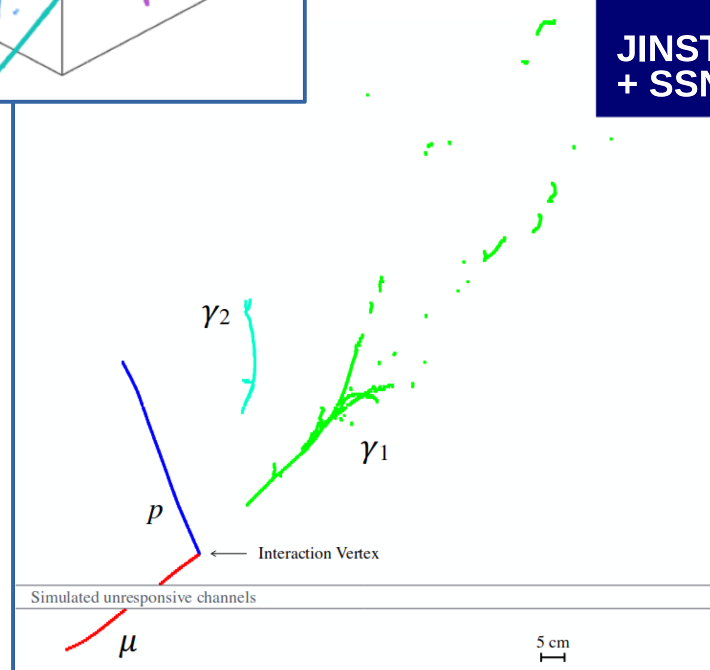


Broad R&D program developing advanced techniques for pattern-recognition employing numerous methods.




Development of pixel-based particle ID via convolutional neural networks



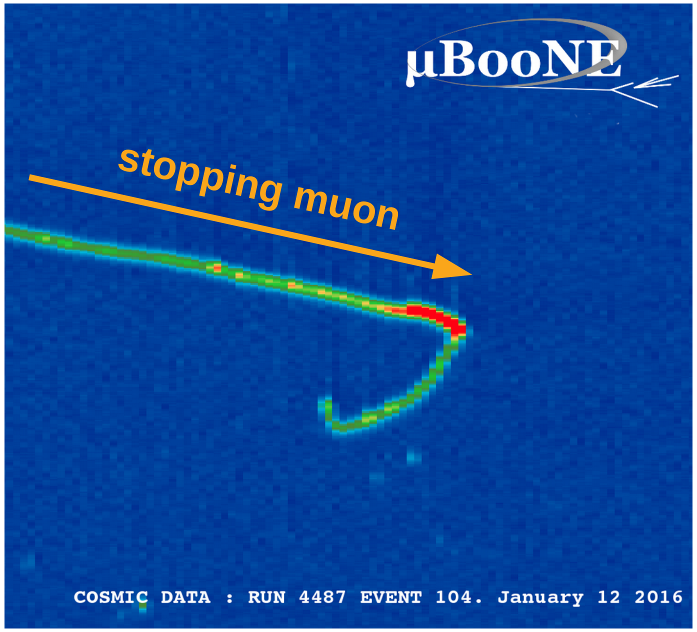



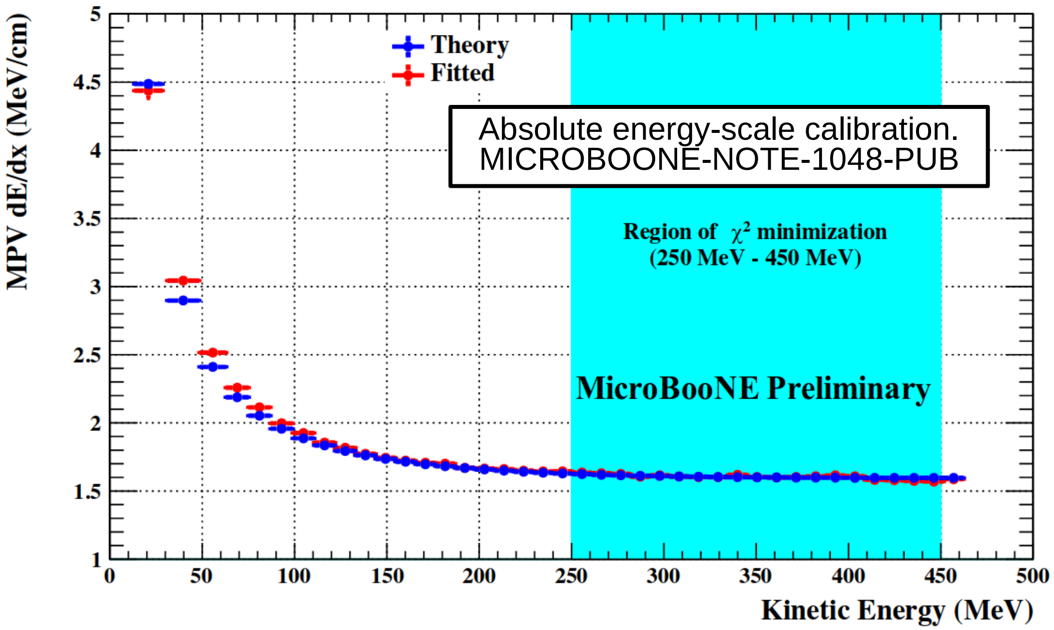

New developments and ideas!

## How to go from high-resolution images to quantitative measurements

## 2) Particle kinematics for physics analyses

# Calibrations



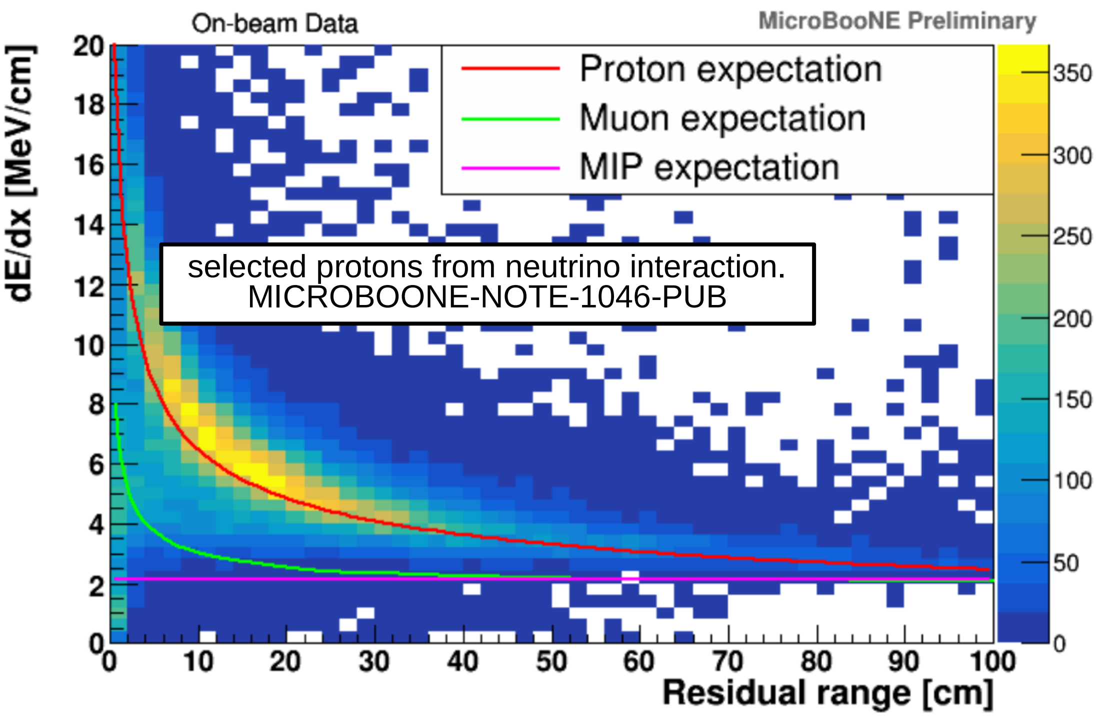




Two-step calibration of energy response:

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

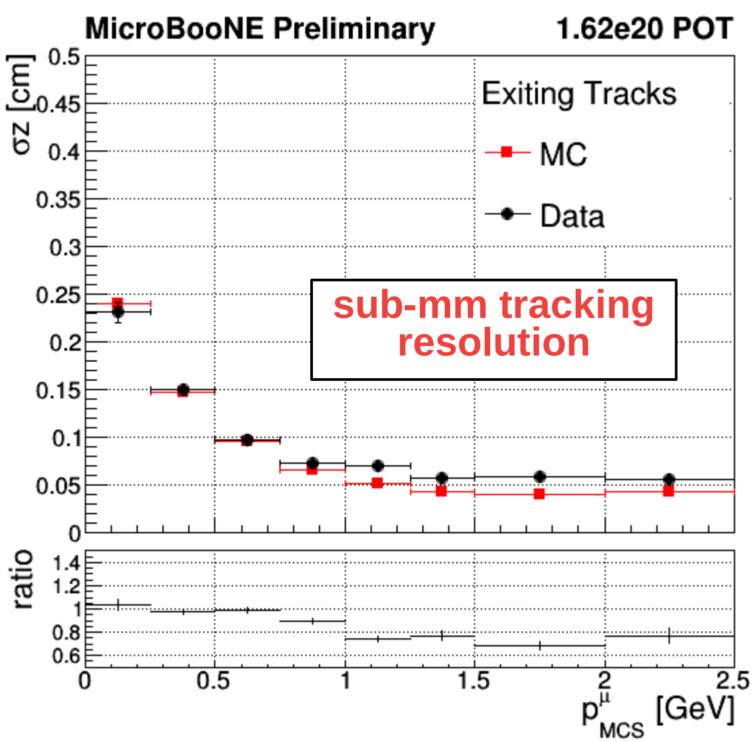
# Tracking performance

**millimiter** 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




# Tracking : Multiple Coulomb Scattering

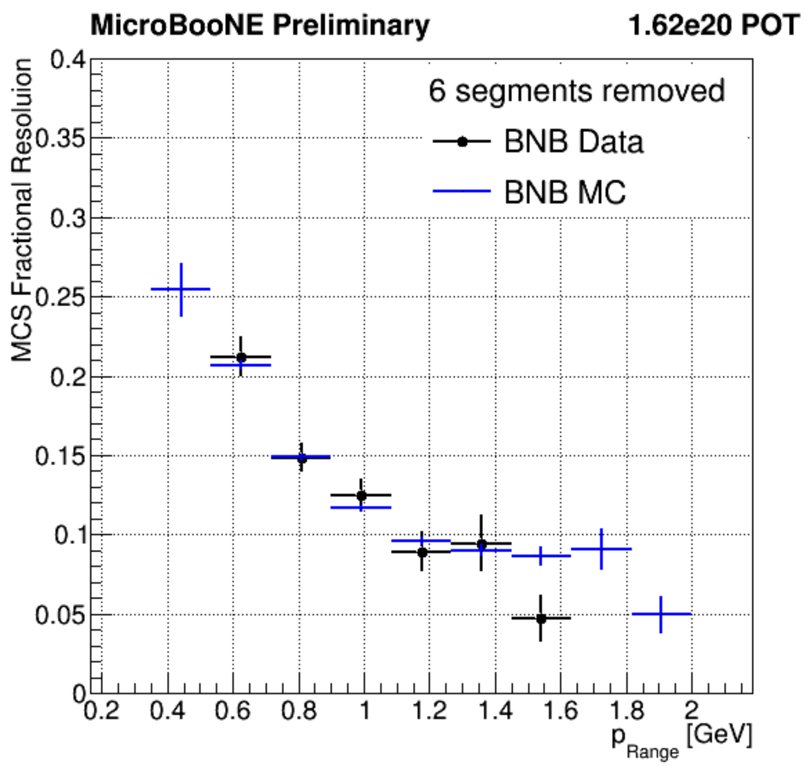
Multiple Coulomb Scattering energy estimation achieves **10% resolution** in MicroBooNE.

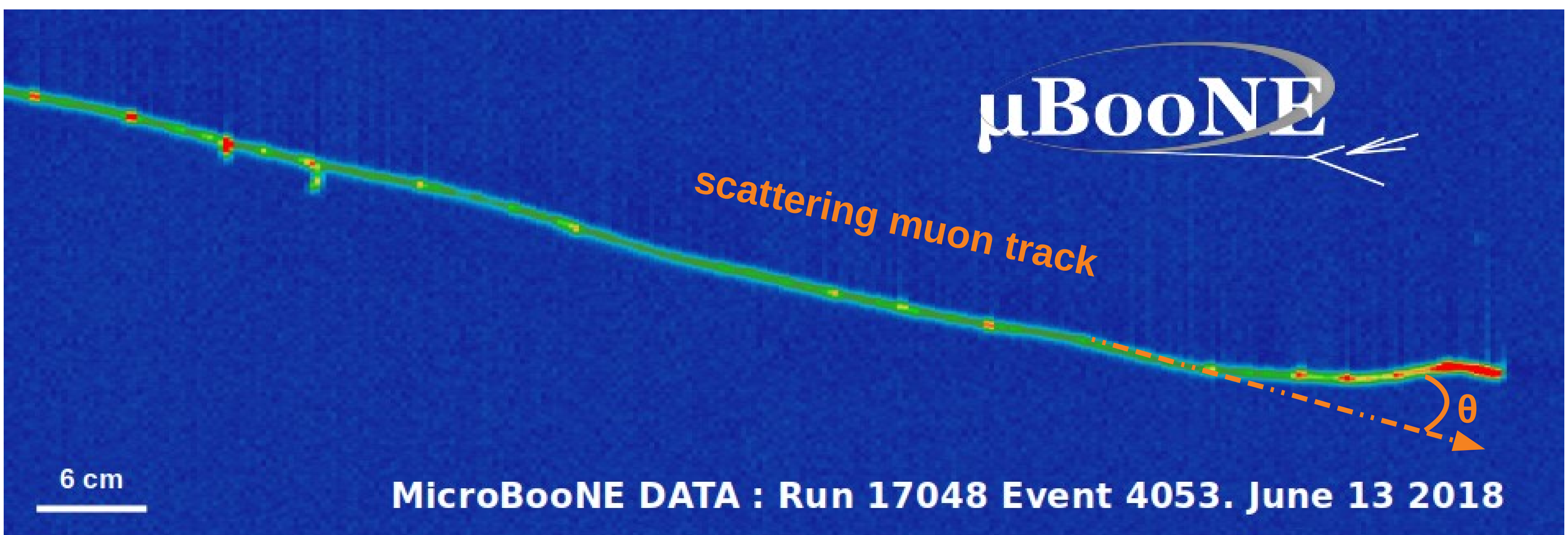
Refined MCS technique specific for argon.

Employed for $\mathbf{P}_{\mu}$ determination in many analyses. Data-driven evaluation of technique.

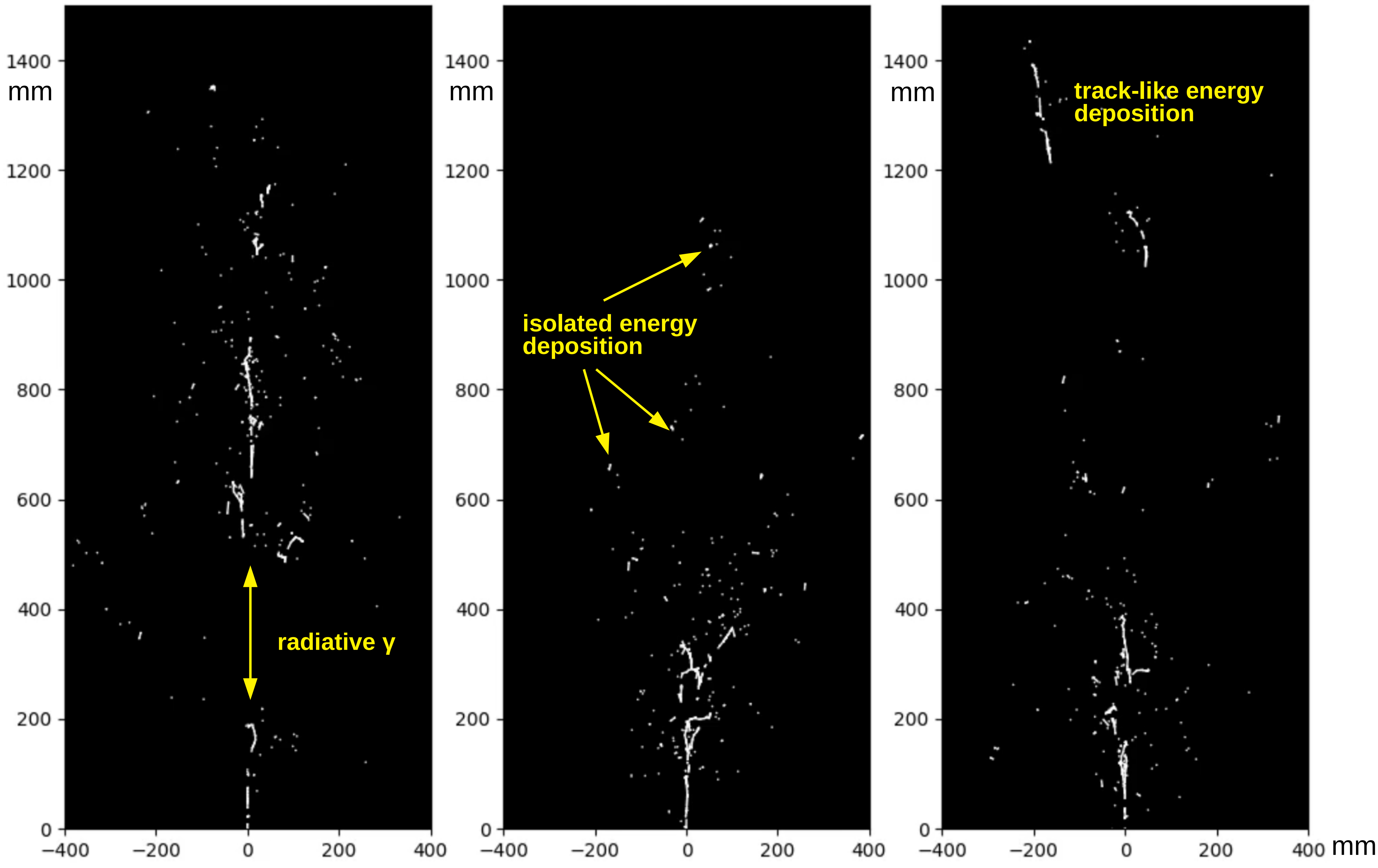
*JINST 12 (2017) P10010*.

Updates on data-driven studies in MICROBOONE-NOTE-1049-PUB



# Calibrating Electromagnetic Interactions




**300 MeV e- showers in LAr**

# Calibrating Electromagnetic Interactions



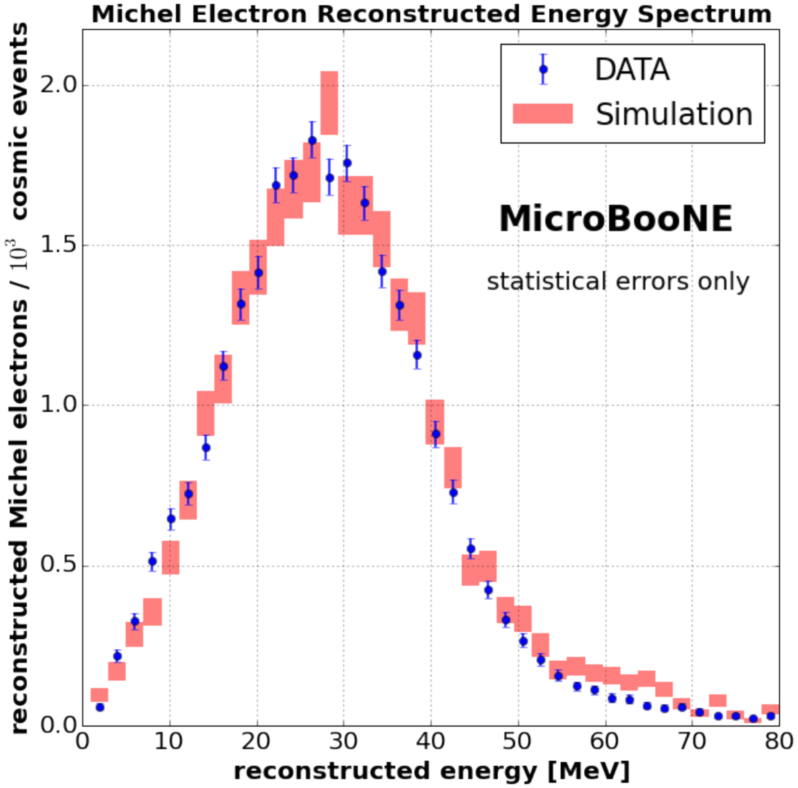
Electron and photon reconstruction is key to oscillation measurements.

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.

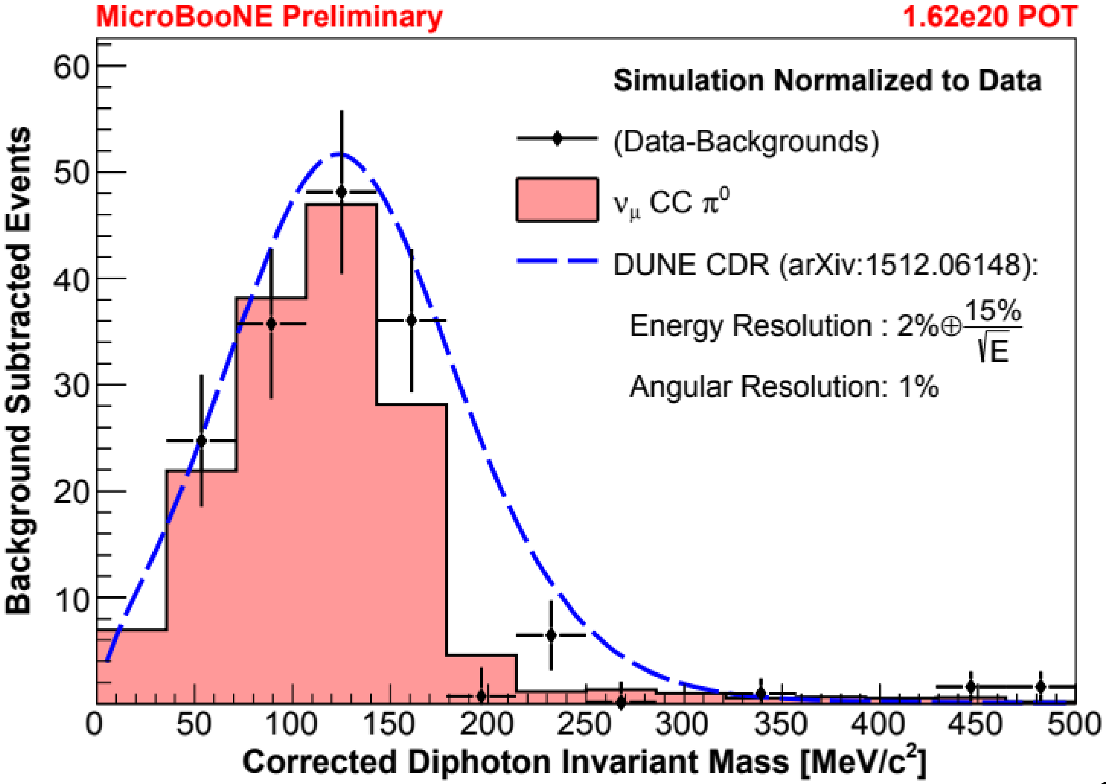
Michel electrons and photons from $\pi^0$ are used for these studies.

*Michel electrons < 50 MeV*




JINST 12 P09014 (2017)

*$\pi^0 \rightarrow$ 30- few hundred MeV*




MICROBOONE-NOTE-1032-PUB

# Conclusions



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.

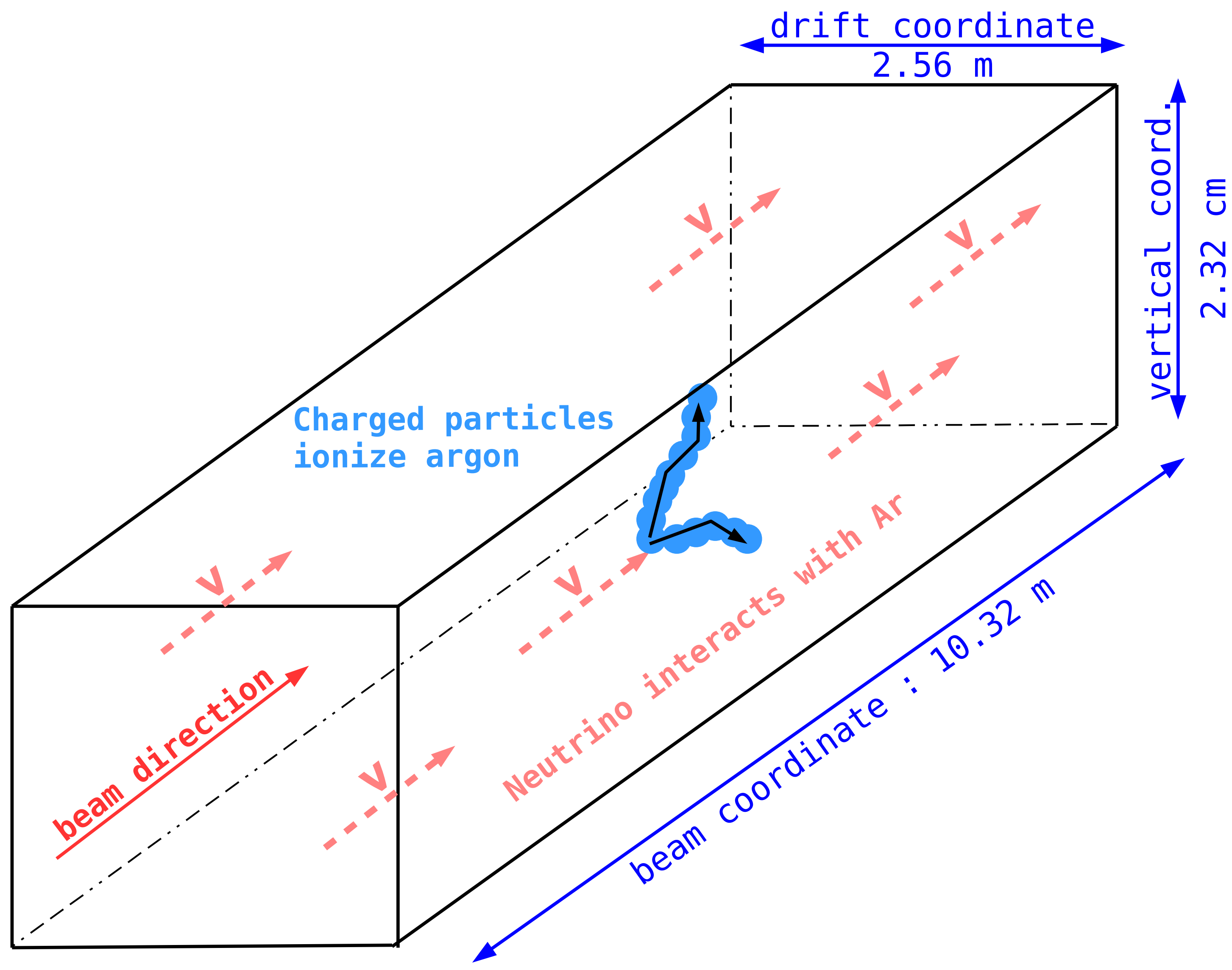
These results directly impact the physics we extract from our detector.

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

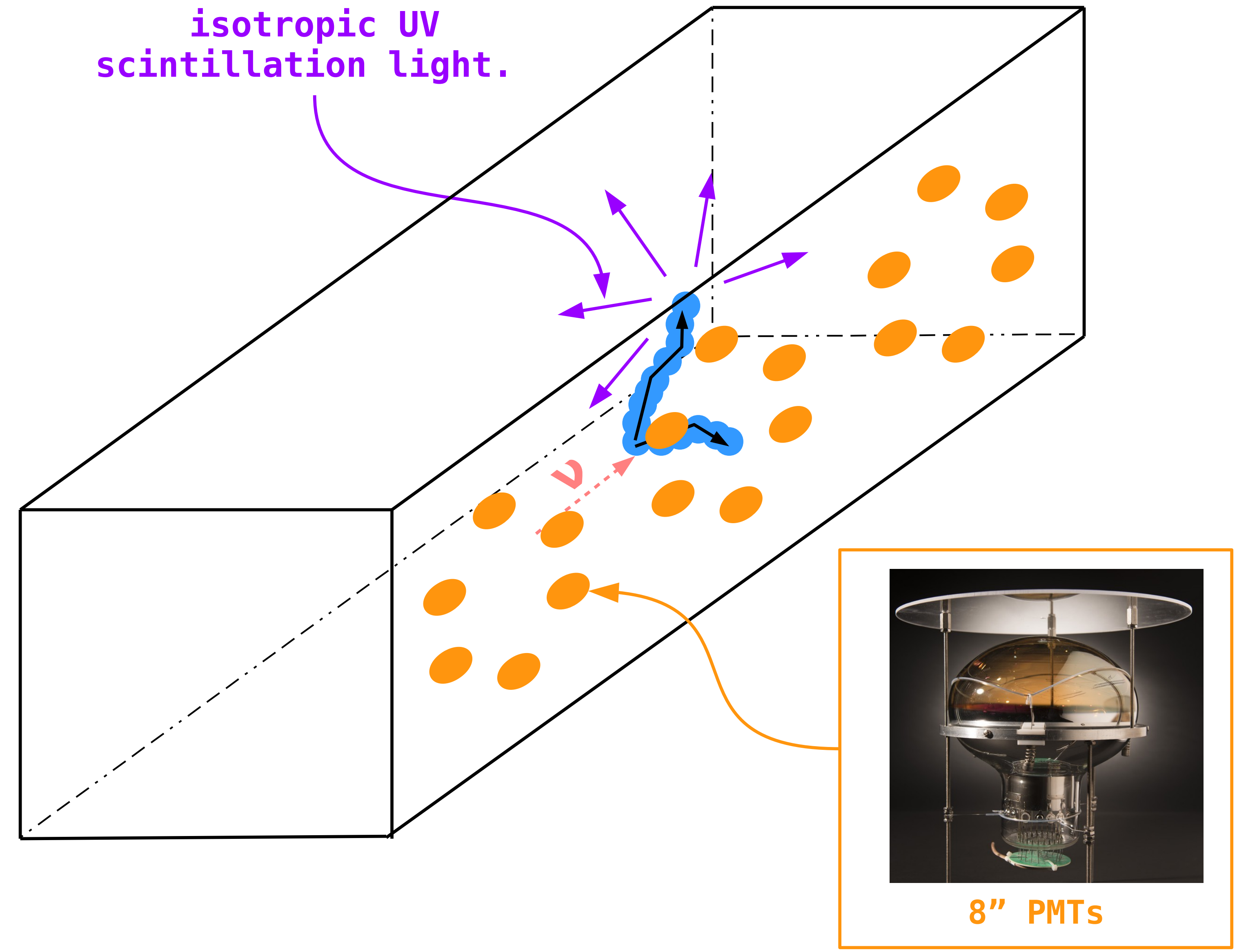
MicroBooNE public notes accessible @ http://microboone.fnal.gov/public-notes/

# Backup

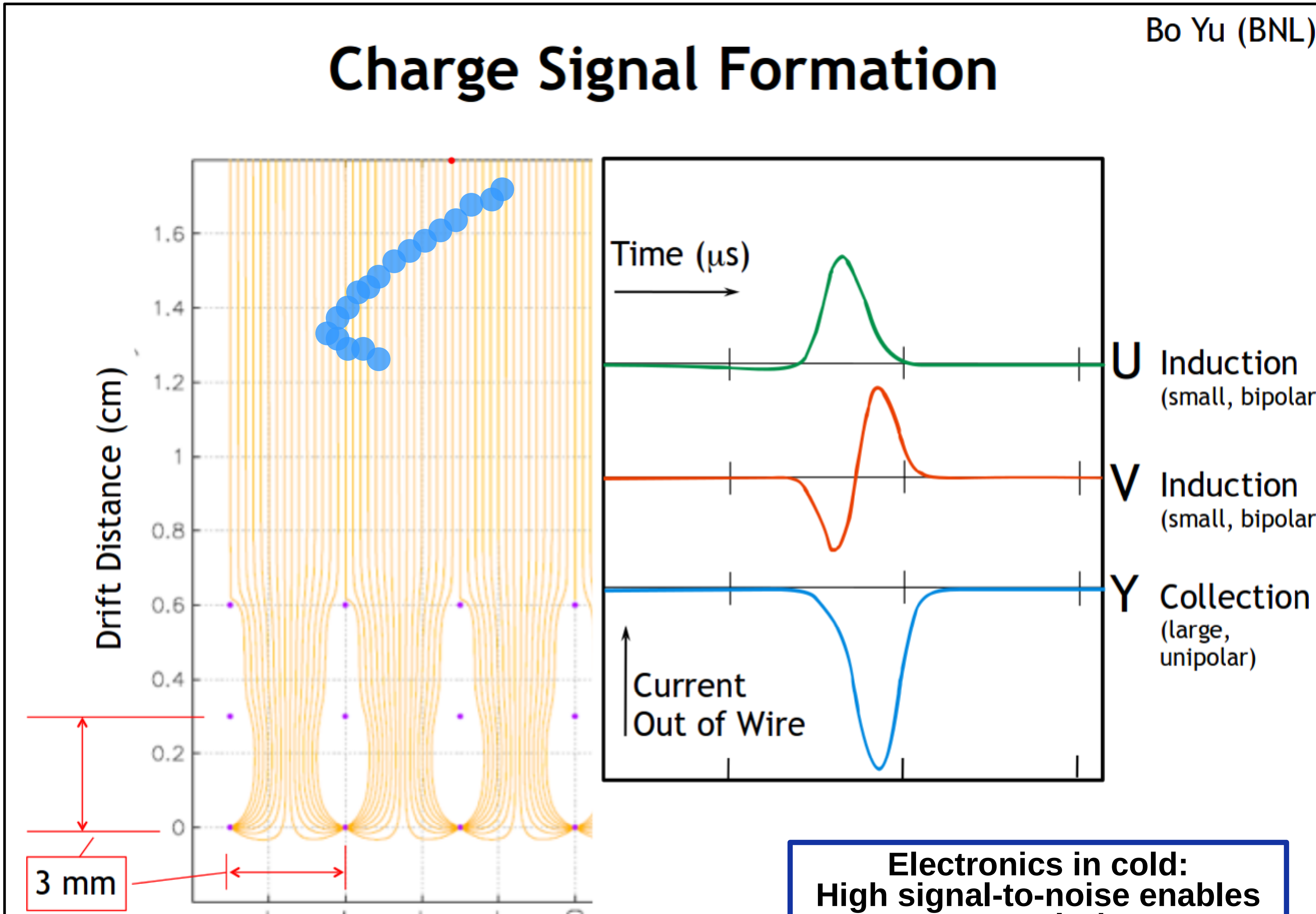
# LArTPC Working Principle



# LArTPC Working Principle

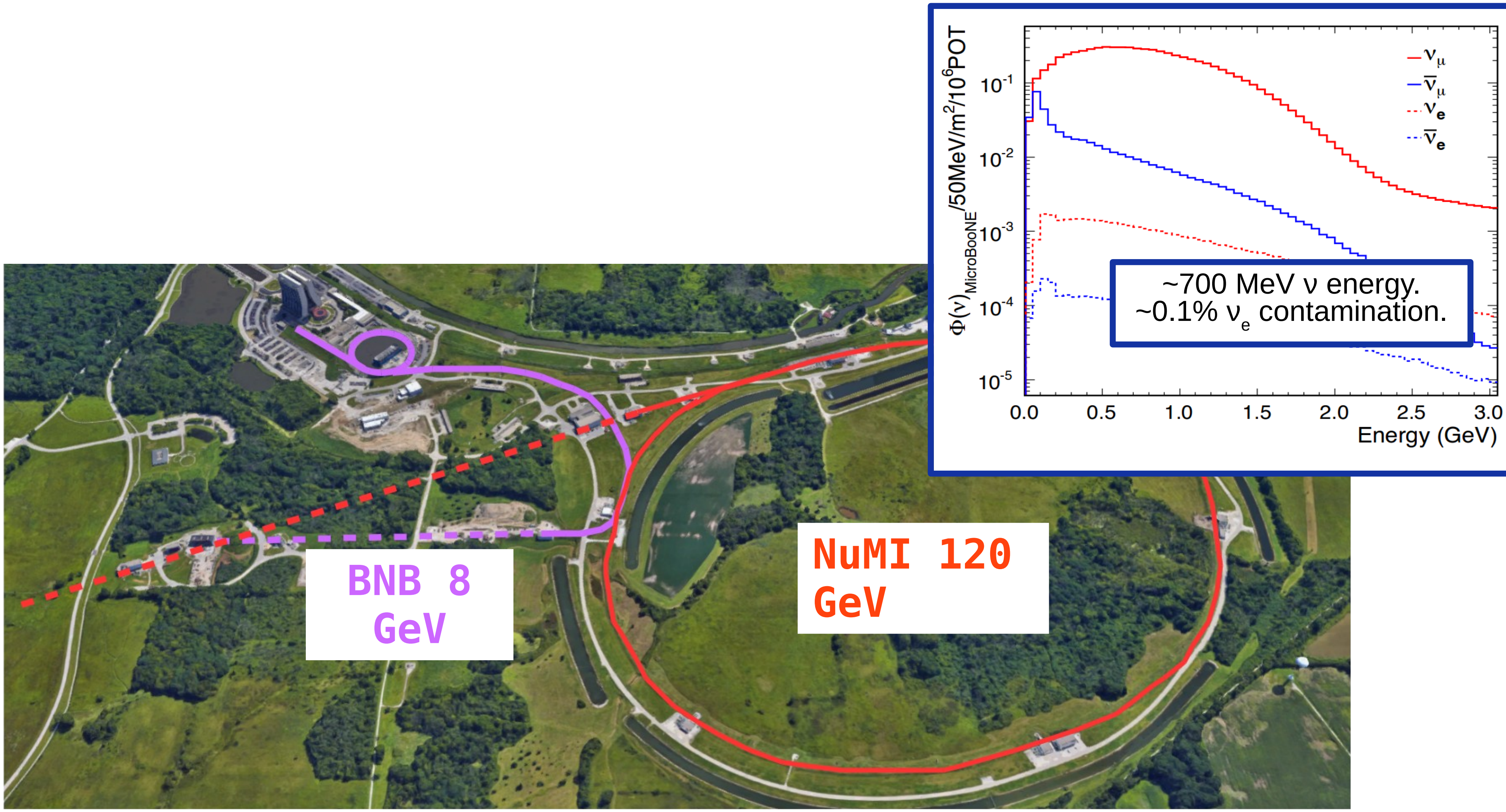


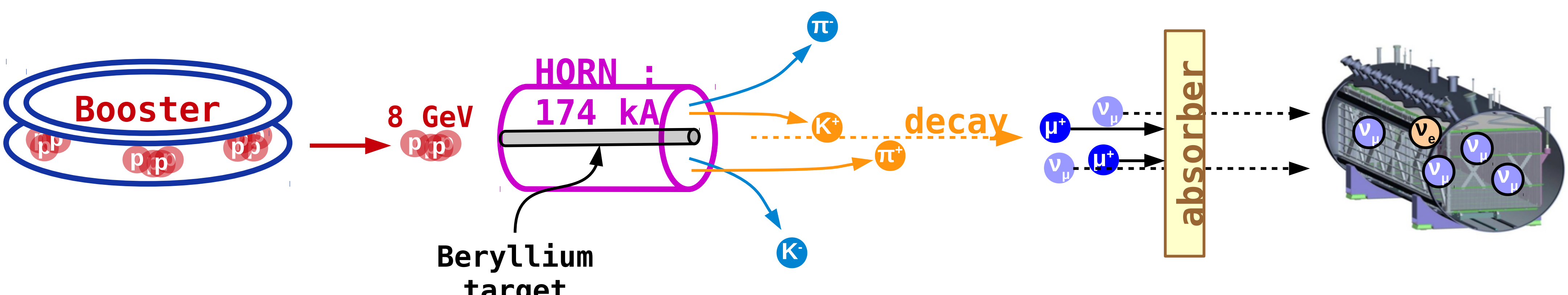
# LArTPC Working Principle




**Electronics in cold:**
**High signal-to-noise enables accurate calorimetry.**

# BNB and NuMI Beamlines



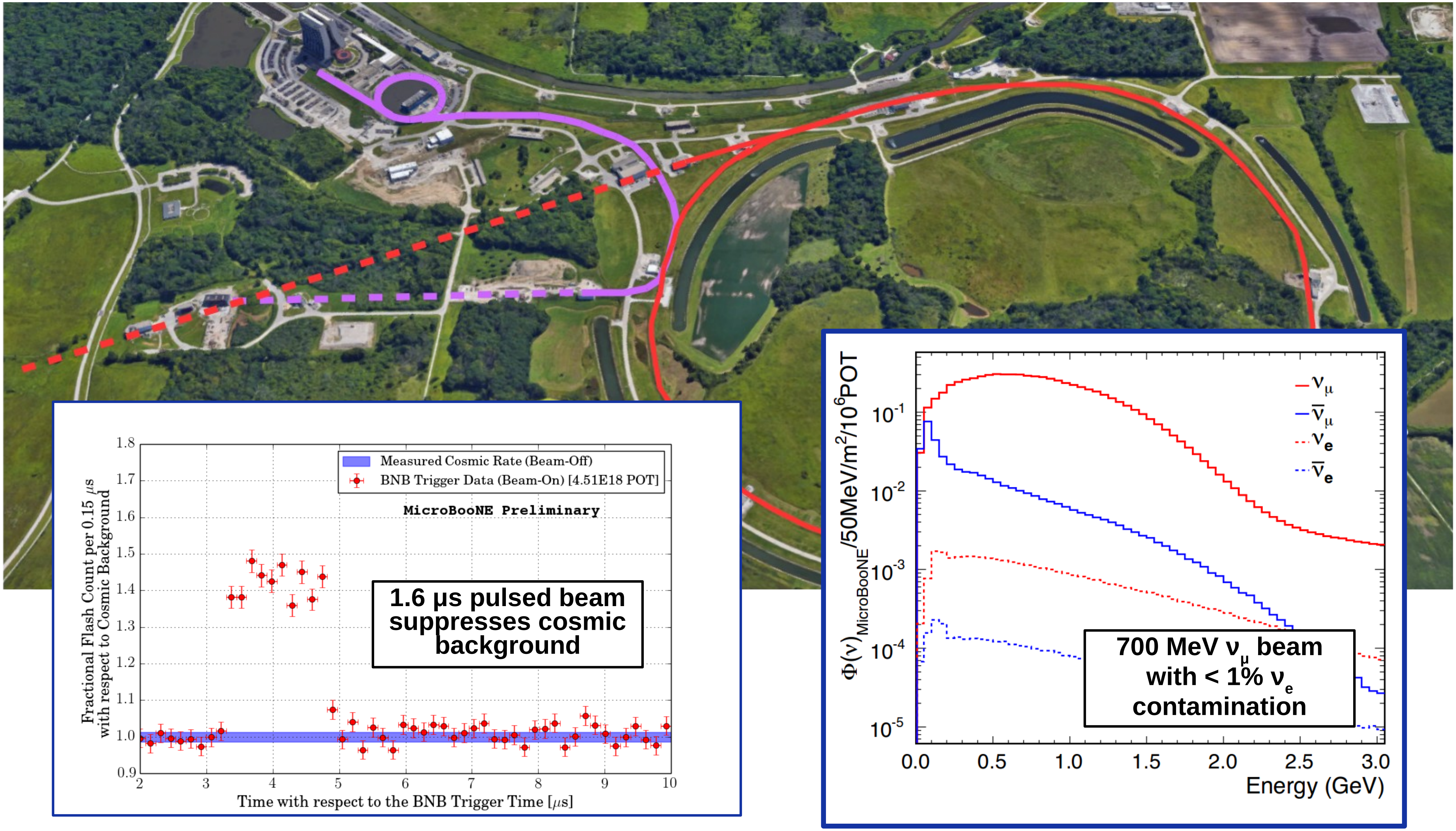



# MicroBooNE’s neutrinos

David Caratelli, Fermilab : ICHEP 2018, Seoul, South Korea

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

O(1 GeV) $\nu_\mu$ beam. 400 meter baseline → L/E ~ 1 eV$^2$.



# Electron Attenuation by Impurities

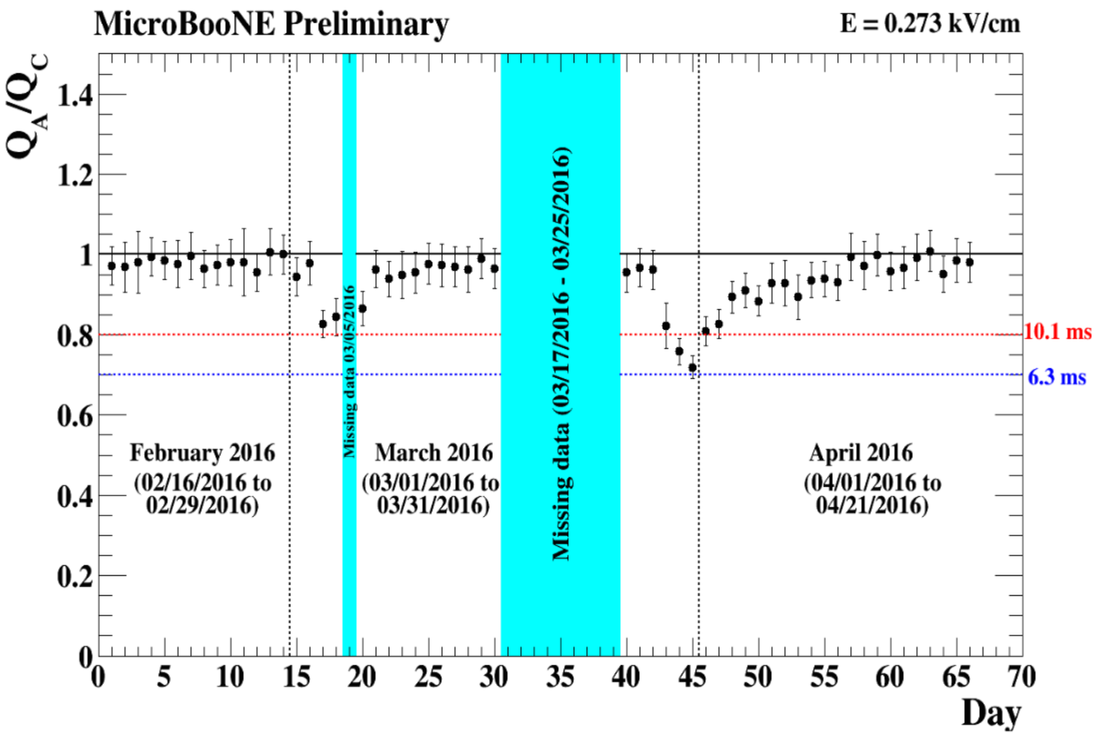
Drifting electrons are absorbed by impurities in the argon.

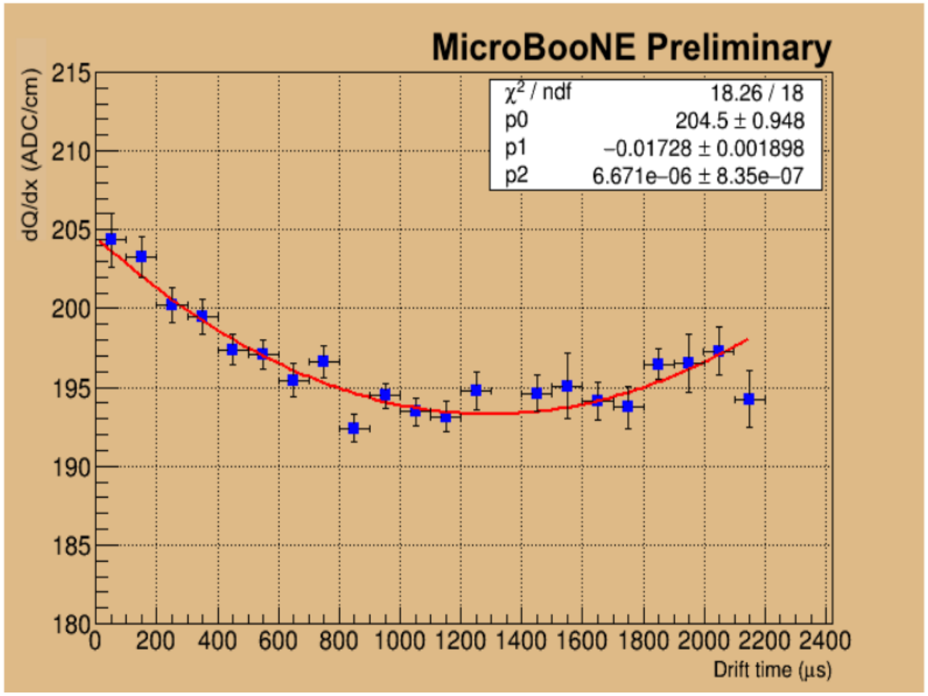
$H_2O$ and $O_2$ are the main sources of e- attenuation.

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.



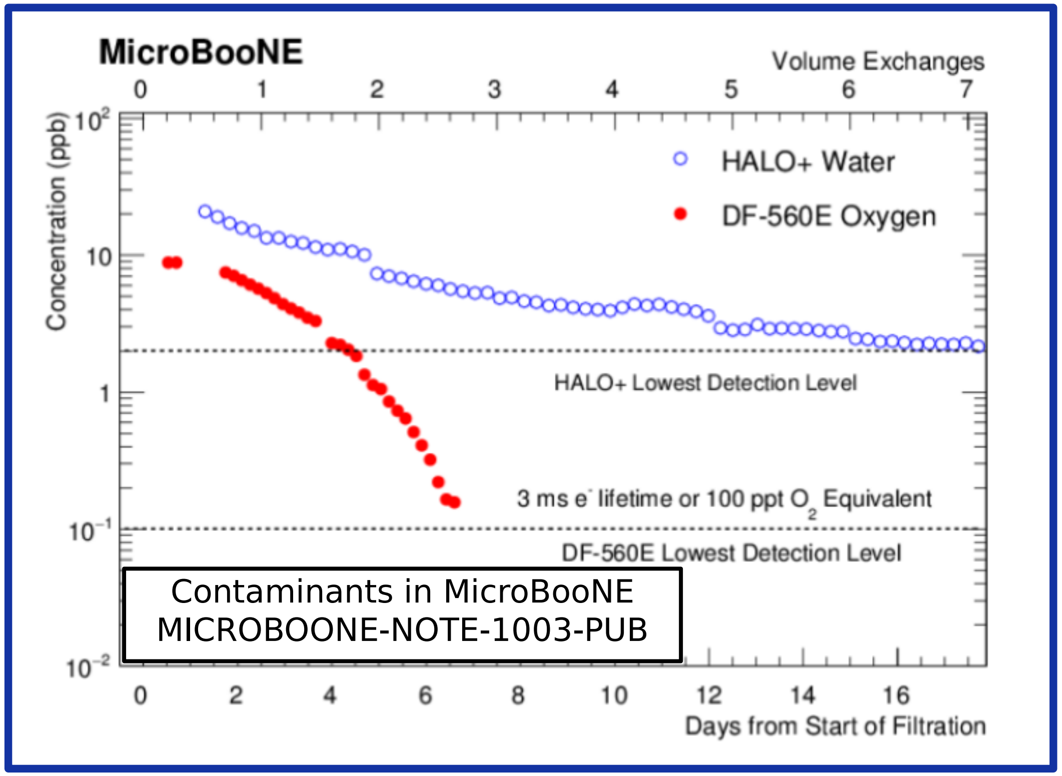




Electron Attenuation in MicroBooNE:
MICROBOONE-NOTE-1026-PUB

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.

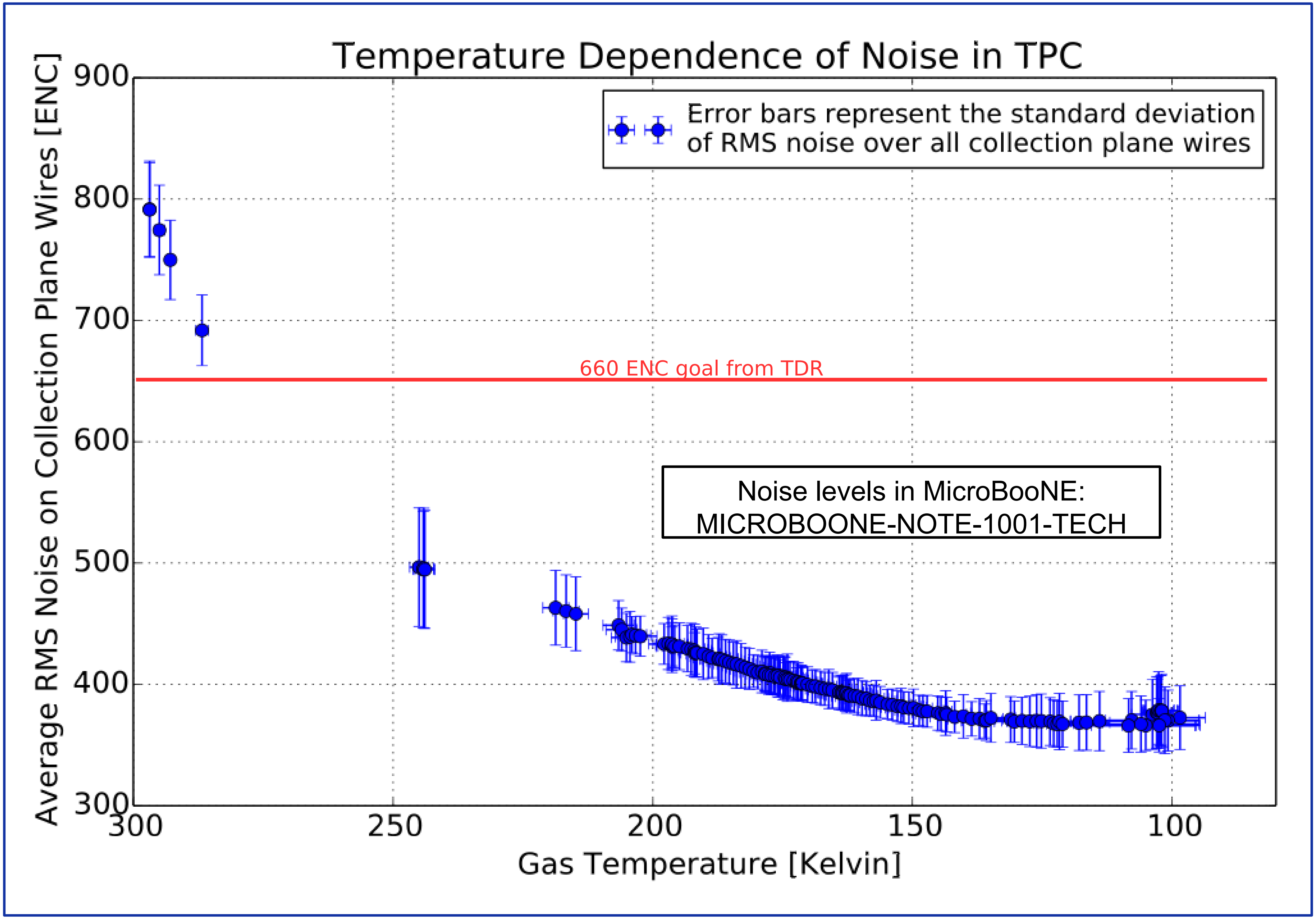
# Argon Purity



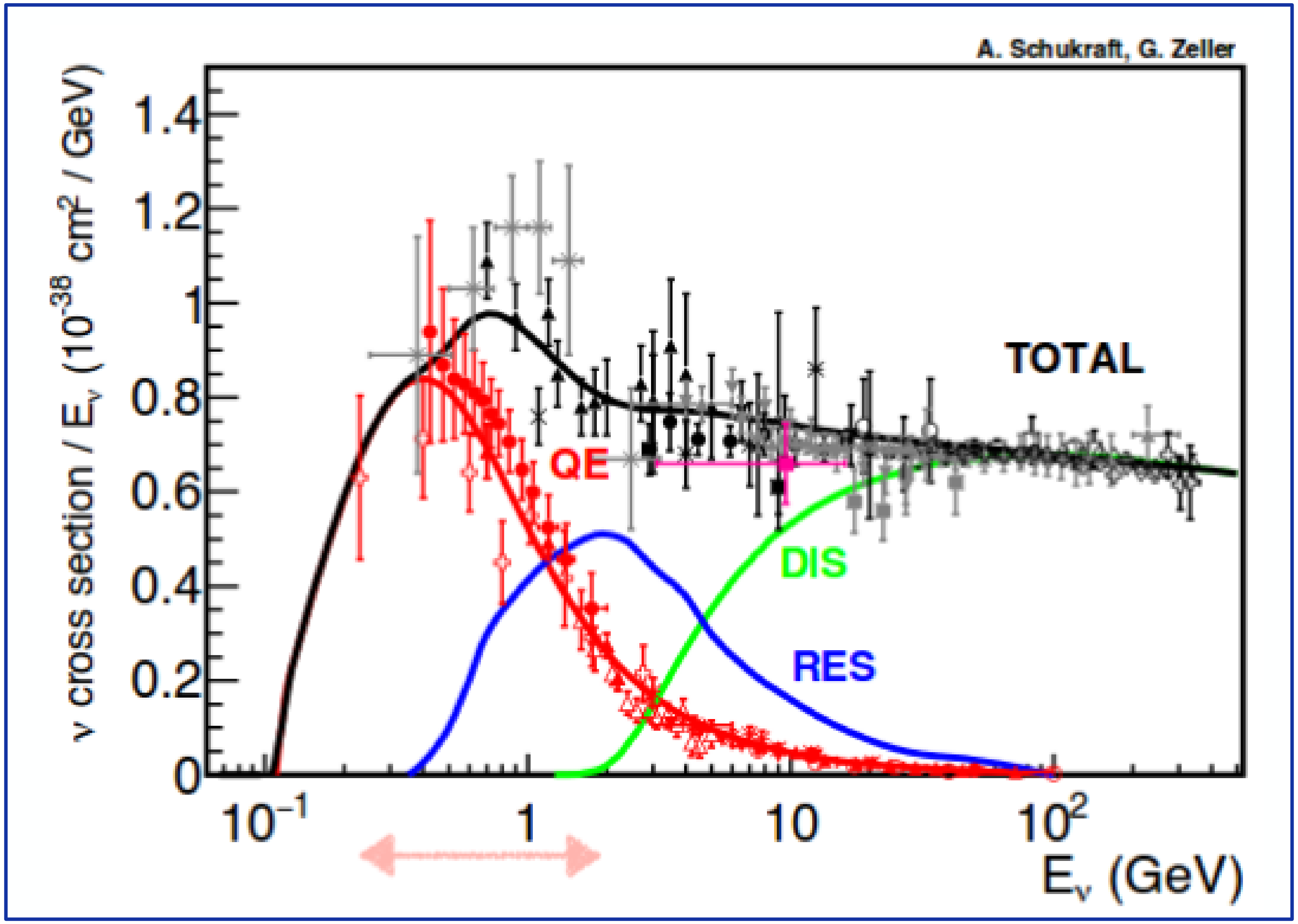

MicroBooNE LAr quality:

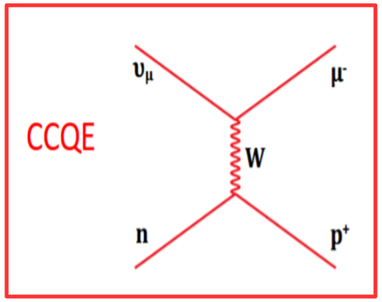
- Air evacuation during commissioning (fill cryostat volume with heavy Ar from bottom → remove impurities in air).
- Recirculation and impurity filtration allow to clean Ar as impurities build up.
- Well beyond our design goal of 3 ms argon lifetime.

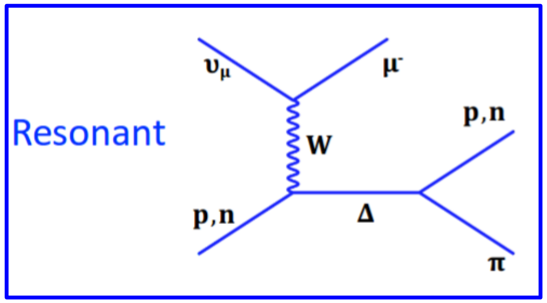
# Electronics Noise

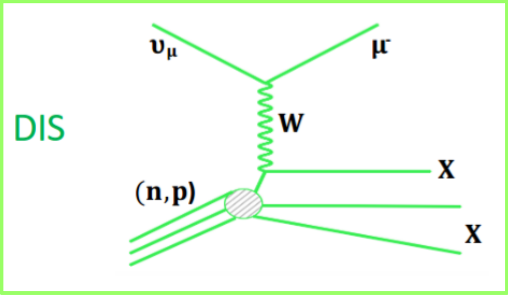


# Interactions in Argon

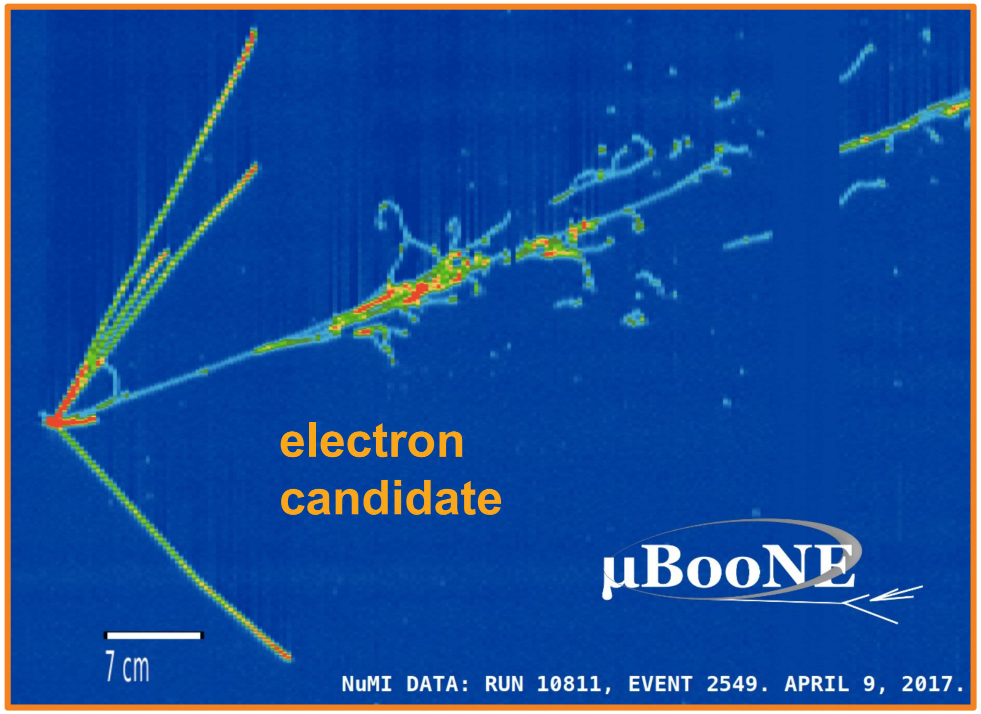


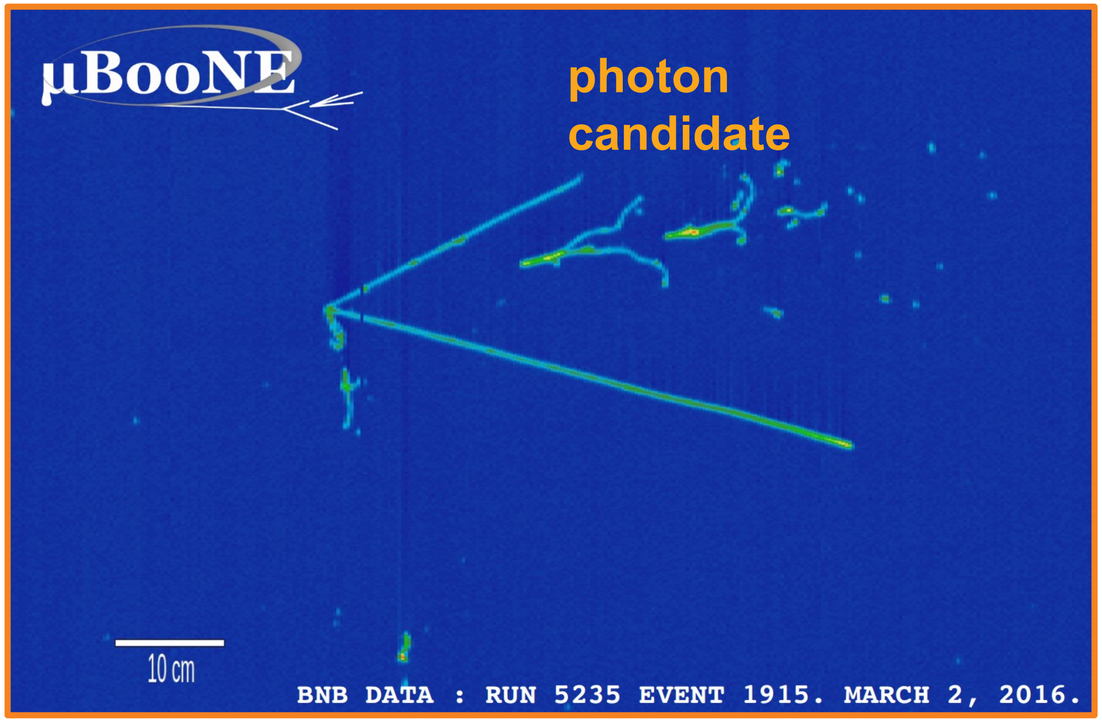



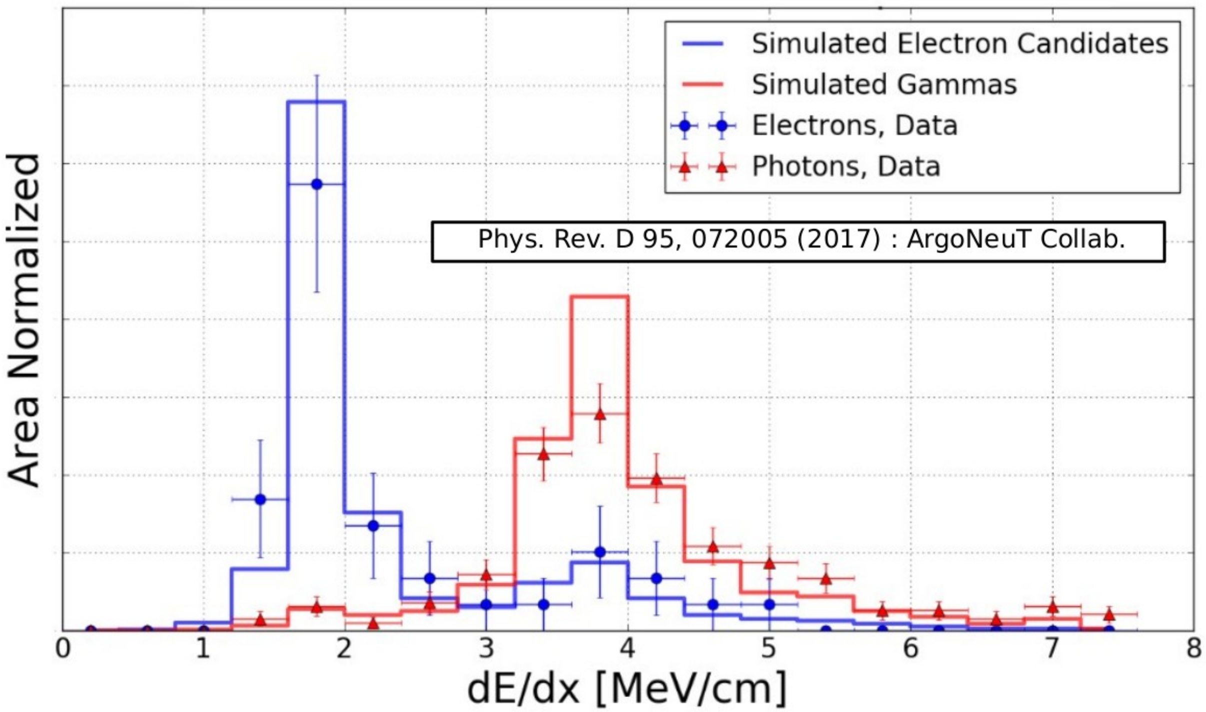



# Electron / Photon Separation



# Electric Field Distortions : Space Charge

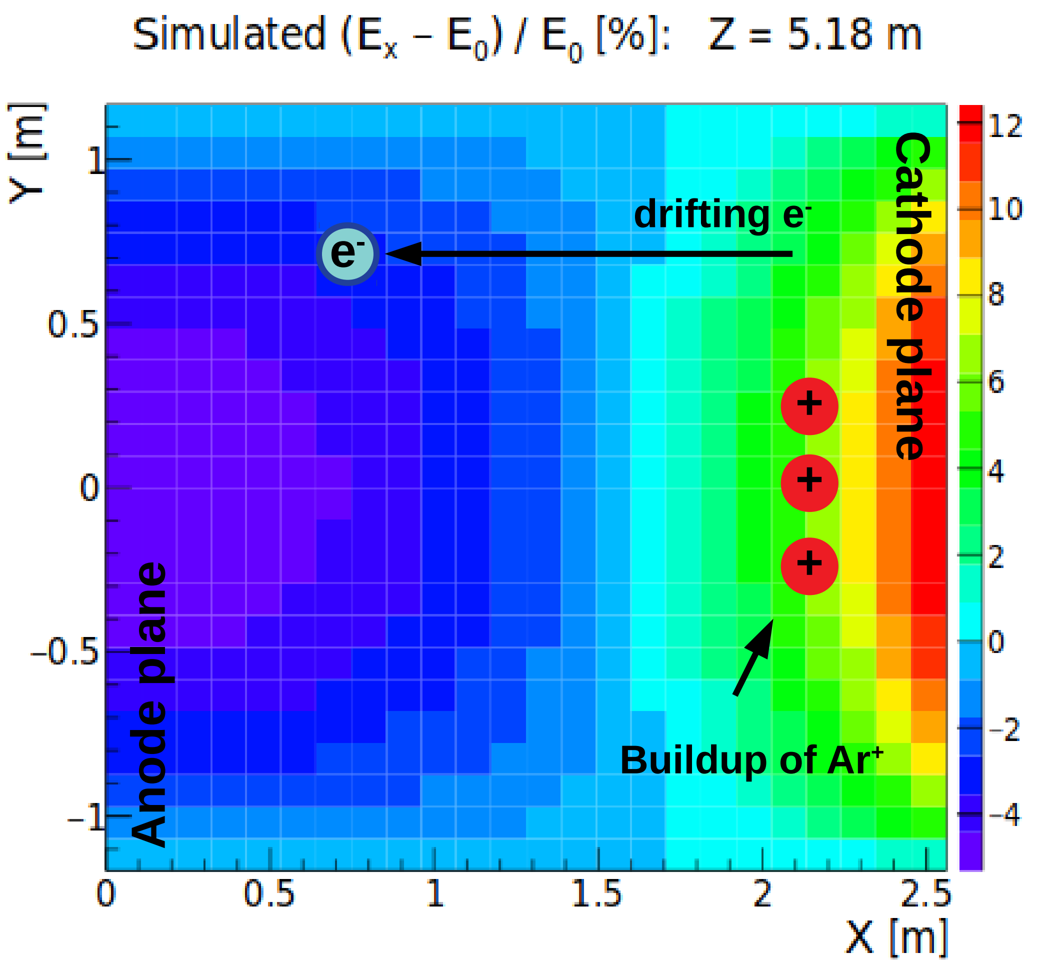
Positive ions drift 105 times slower then e- in Lar.

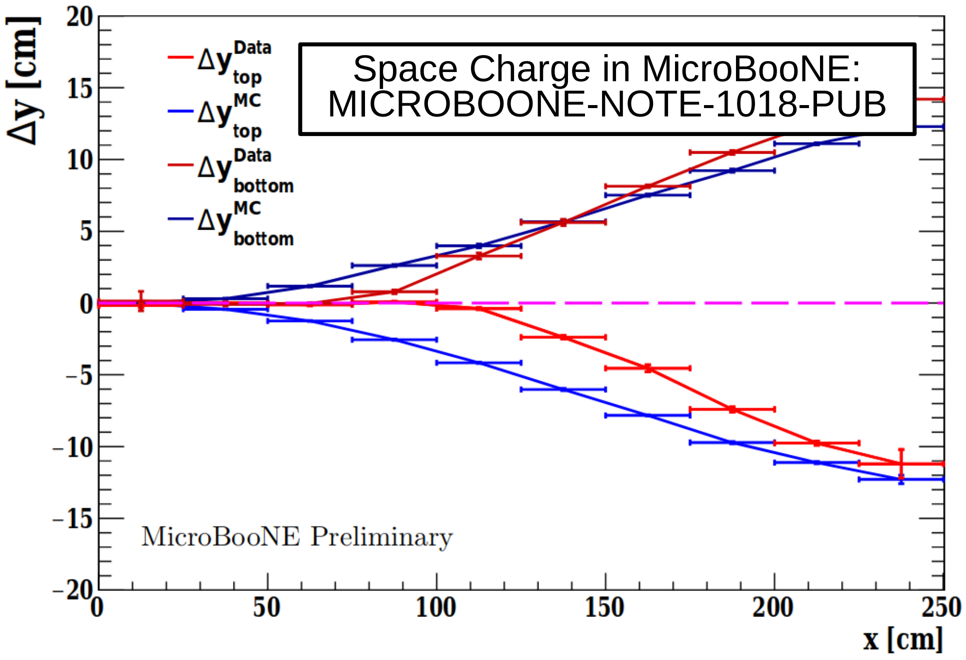
Buildup of Ar+ in TPC in steady-state configuration.

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

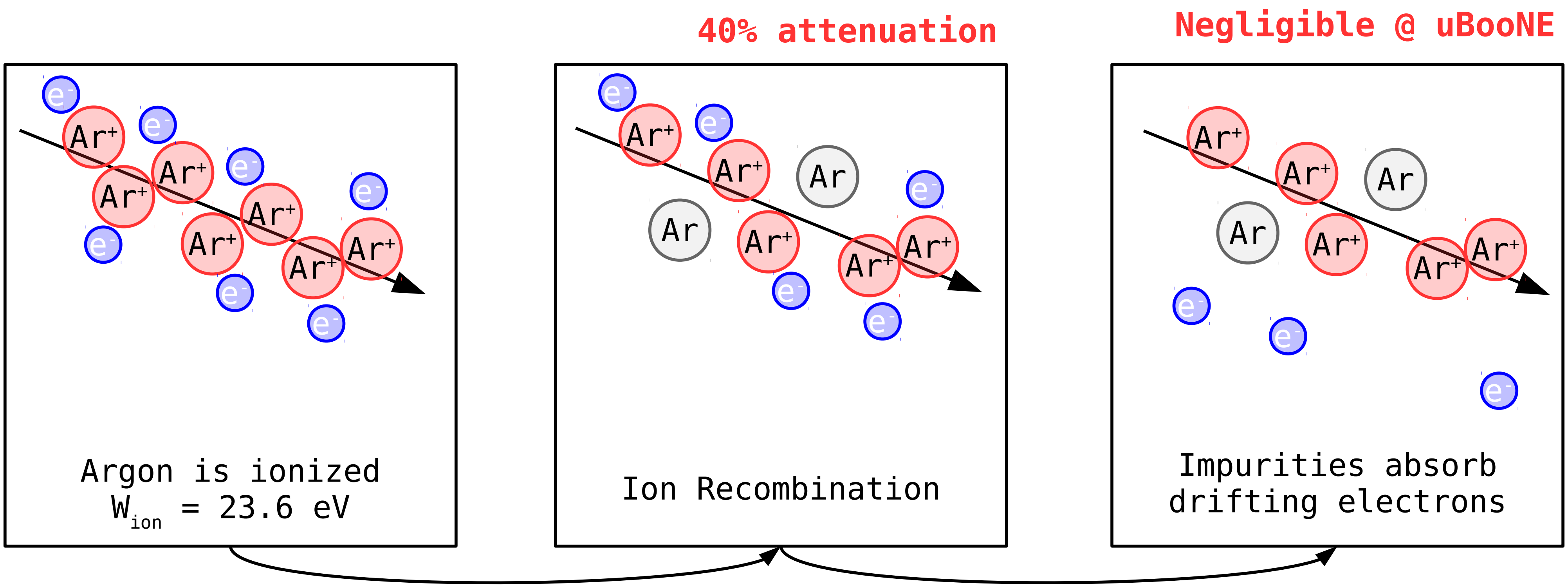
Physics of energy loss in LAr:

Argon is ionized by traversing charged particles.

Positive ions recombine with $e^-$ → signal loss.

Impurities capture drifting $e^-$s → signal loss.

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



# Ion Recombination

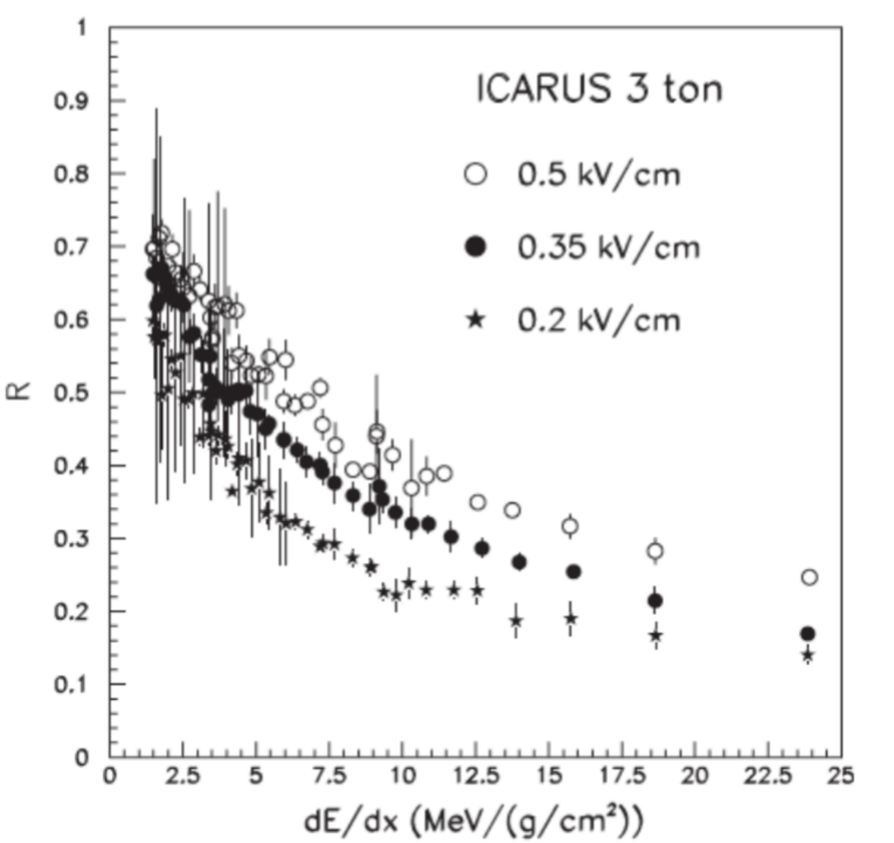
**Box model**

$$dE/dx = \frac{dQ/dx}{A_B/W_{ion} - k_B \cdot (dQ/dx)/\mathscr{E}}.$$

$$\mathscr{R}_{\text{ICARUS}} = \frac{A_B}{1 + k_B \cdot (dE/dx)/\mathscr{E}}$$

**Birks model**

Nuclear Instruments and Methods in Physics Research A 523 (2004) 275–286




Recombination depends on density of $Ar^+$ and $e^-$.

Affected by:

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

For electrons / photons much smaller variation in dE/dx vs. energy compared to muons/protons/pions.

→ significant effect, but ~constant.

# Michel Electrons

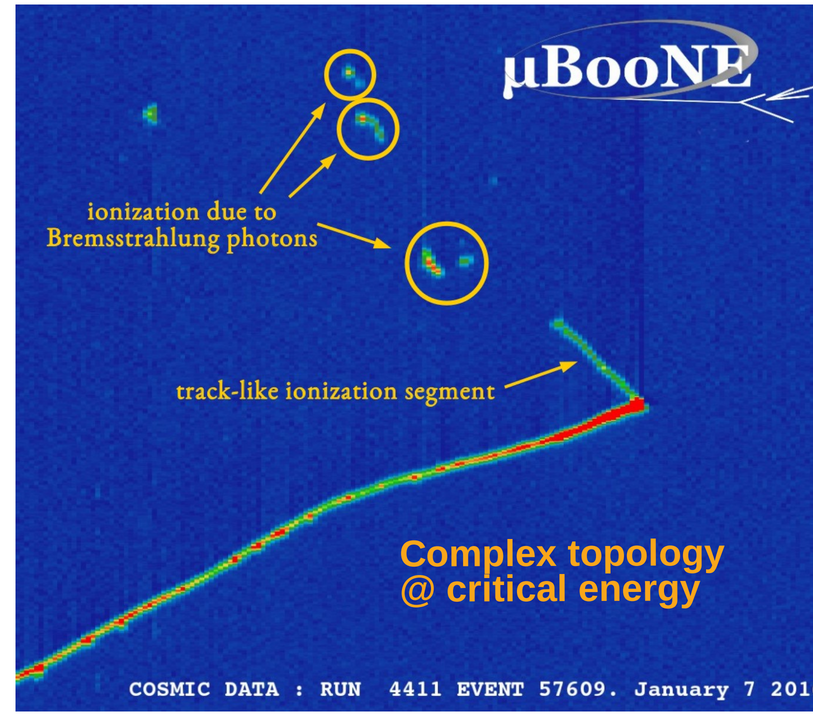


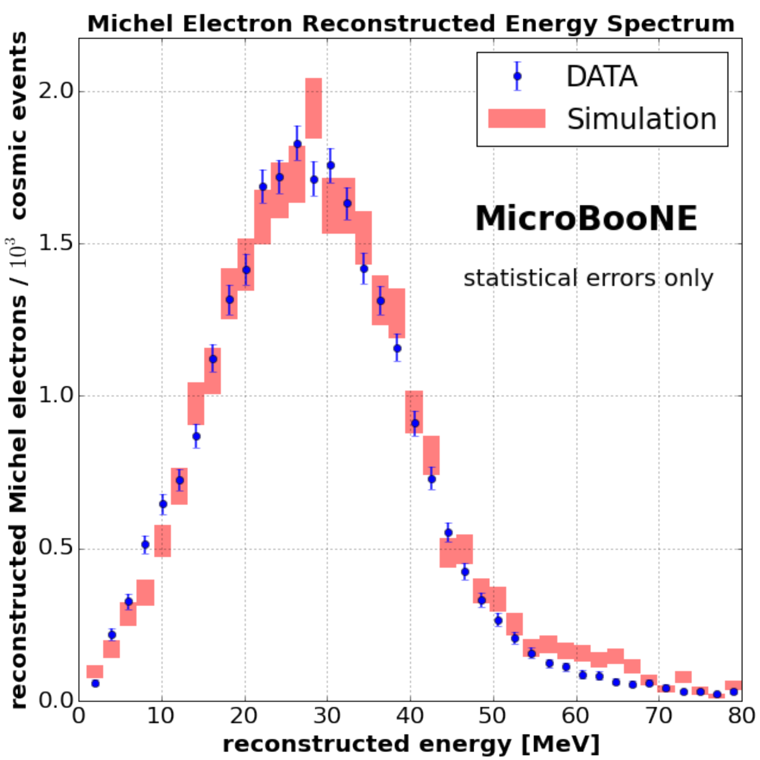
Abundant sample of Michel electrons from decay-at-rest cosmic-ray muons.

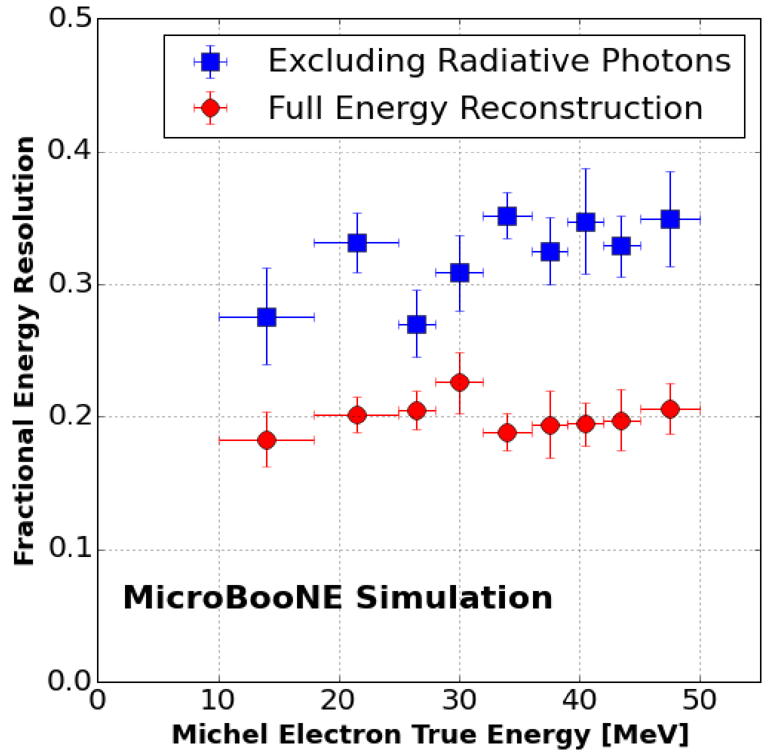
Valuable sample to study EM interactions near the critical energy.

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

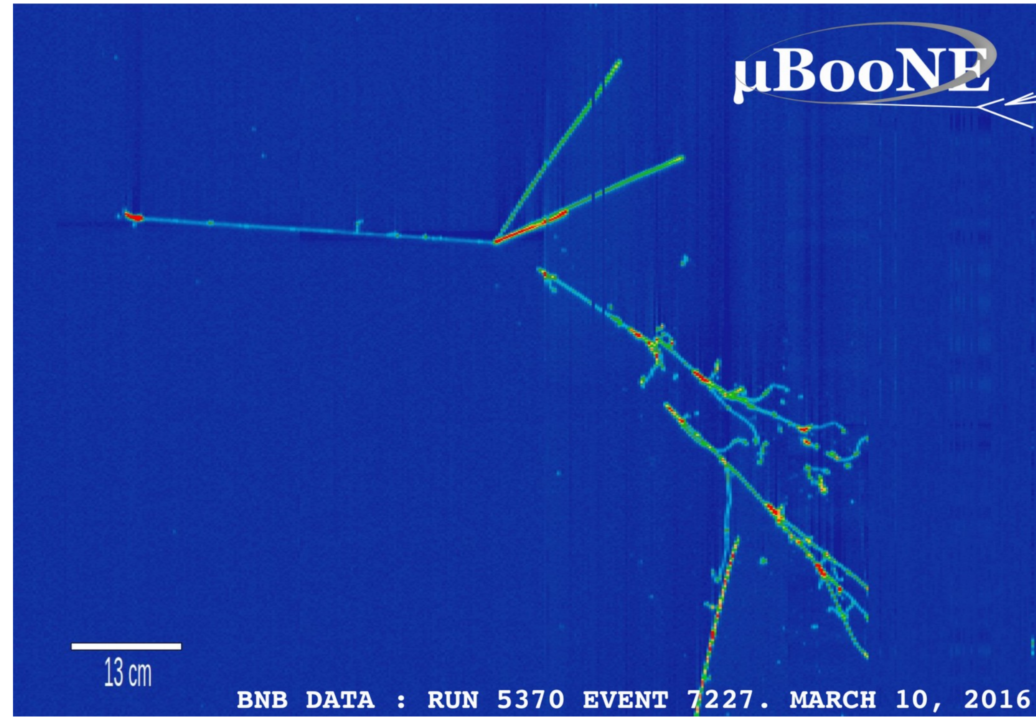


Tens to hundreds of MeV energy range photon showers.

$\pi^0$ 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.

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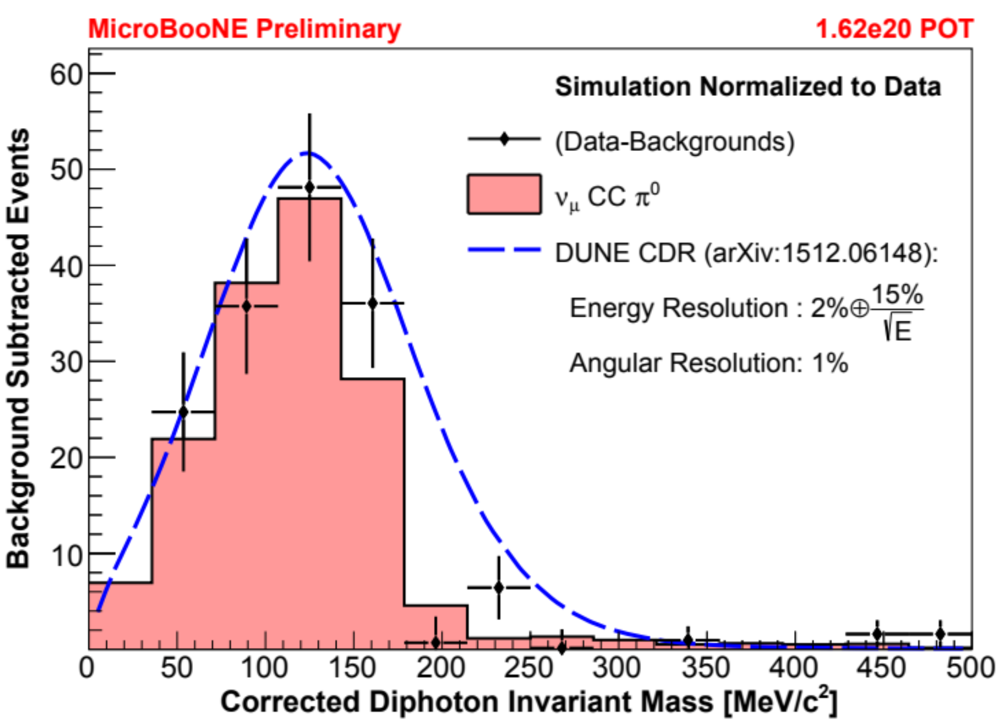
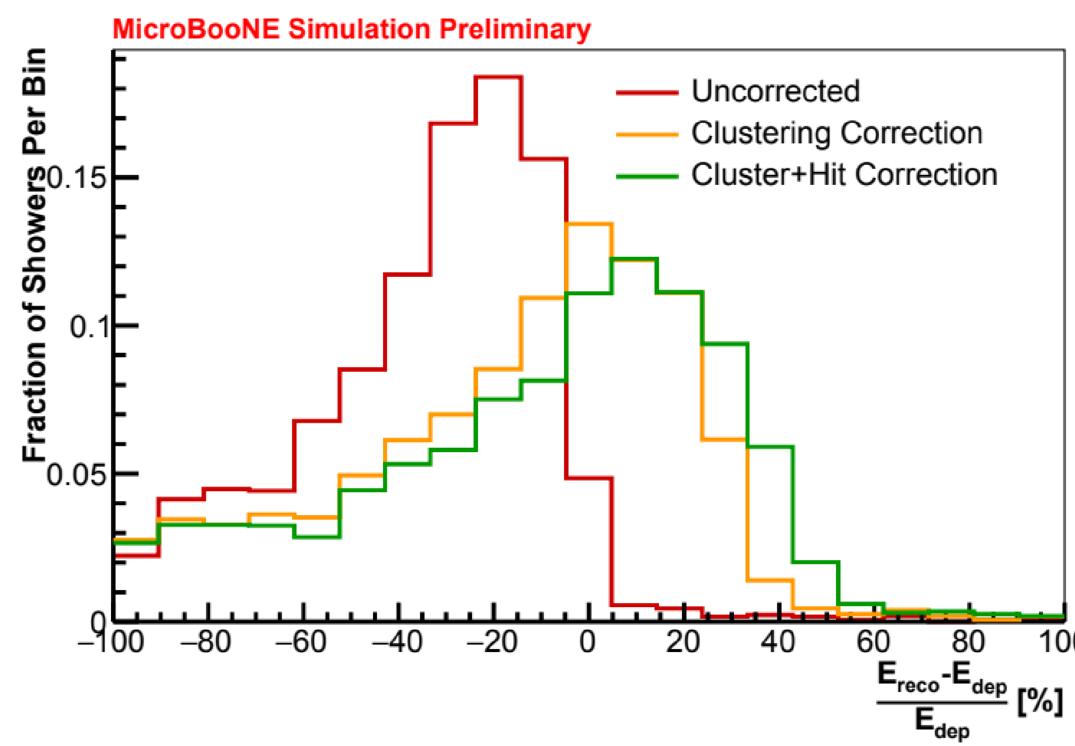
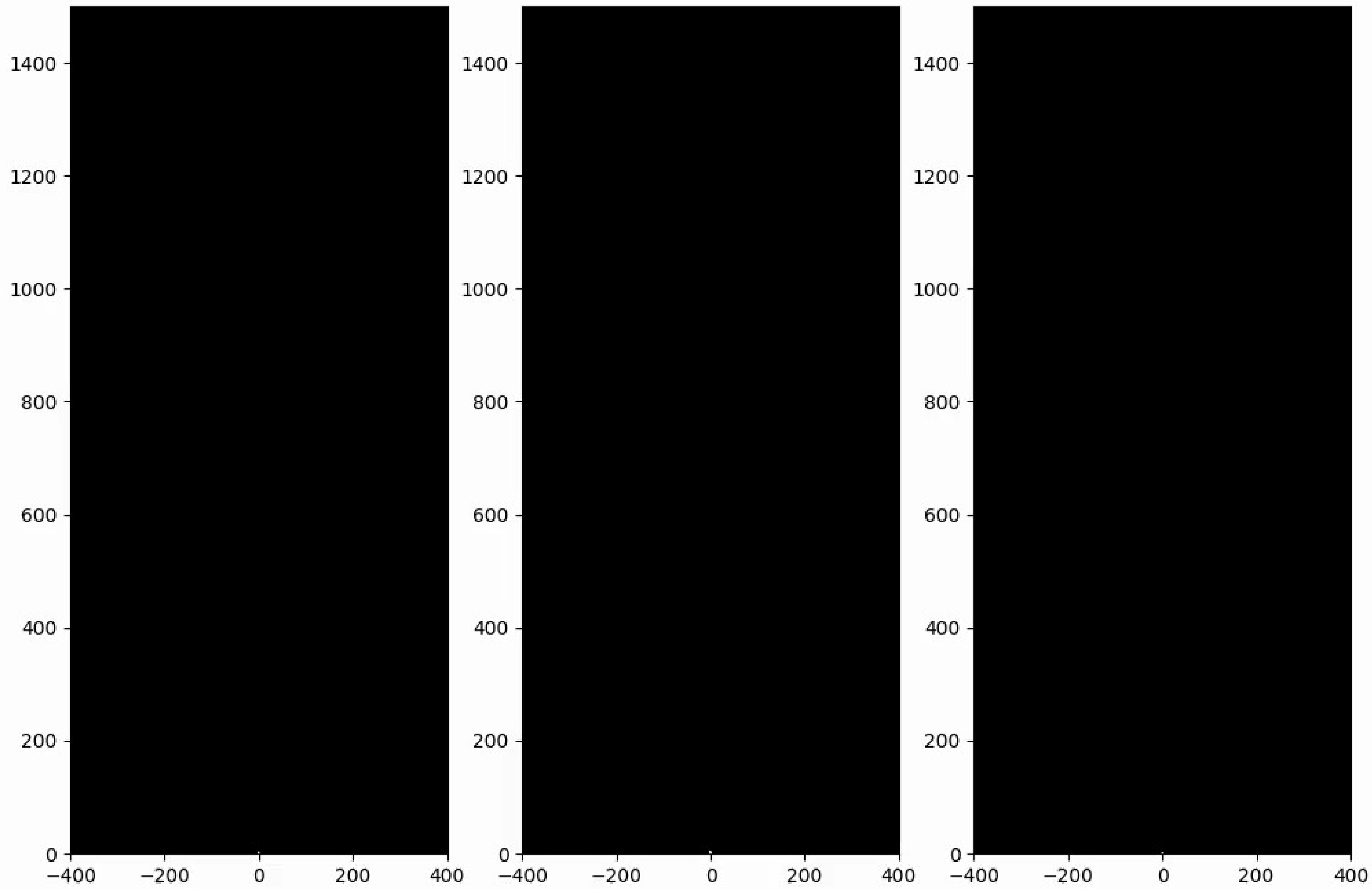
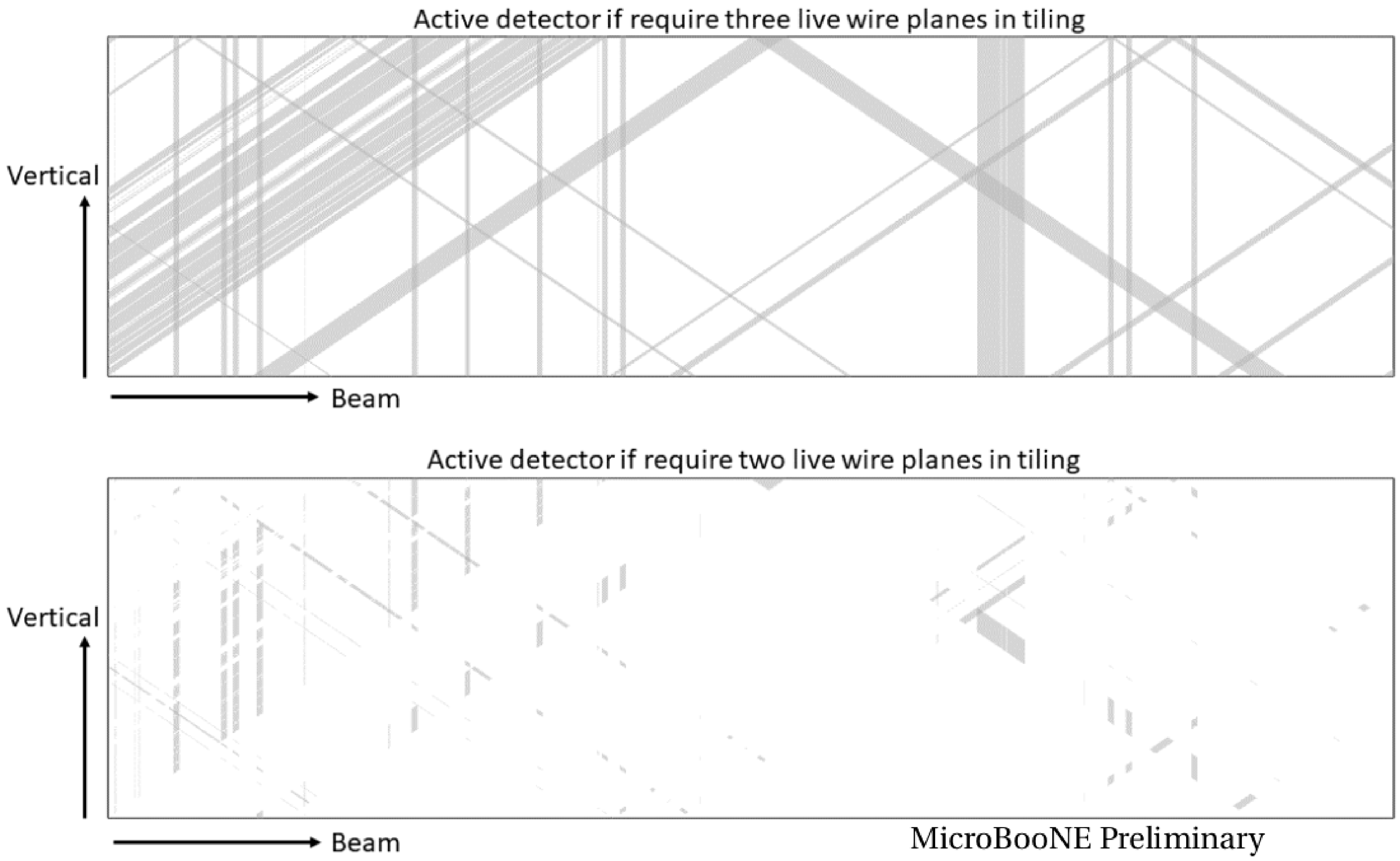


# Calibrating Electromagnetic Interactions



# 3D Coverage

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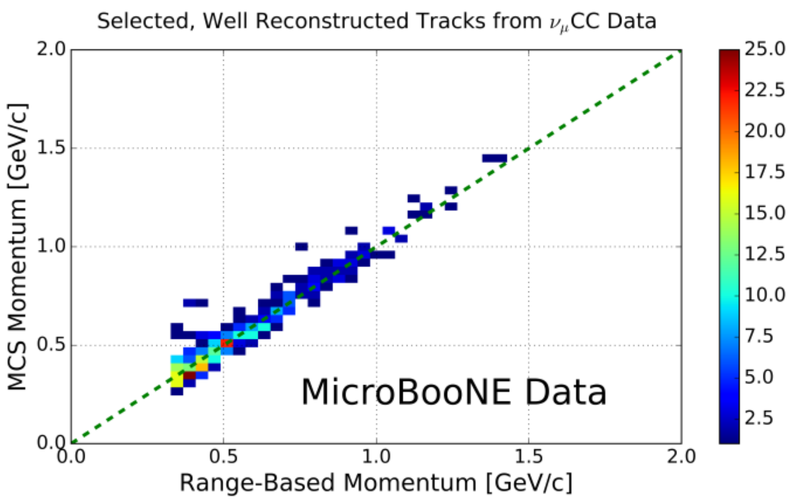
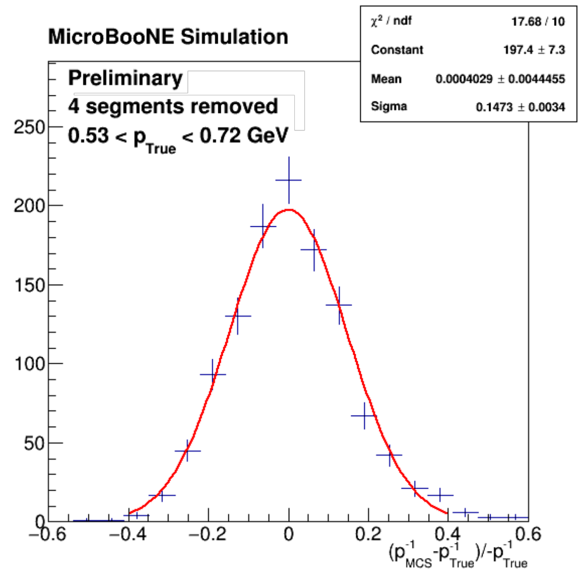
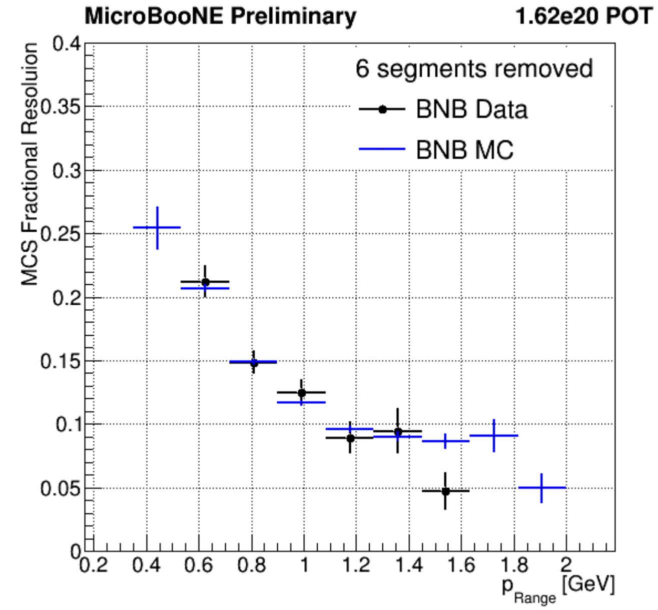
# Tracking : Multiple Coulomb Scattering




Multiple Coulomb Scattering energy estimation achieves **10% resolution** in MicroBooNE.

Employed for $\mathbf{P}_\mu$ determination in many analyses. Data-driven evaluation of technique.

JINST 12 (2017) P10010.  Updates on data-driven studies in MICROBOONE-NOTE-1049-PUB