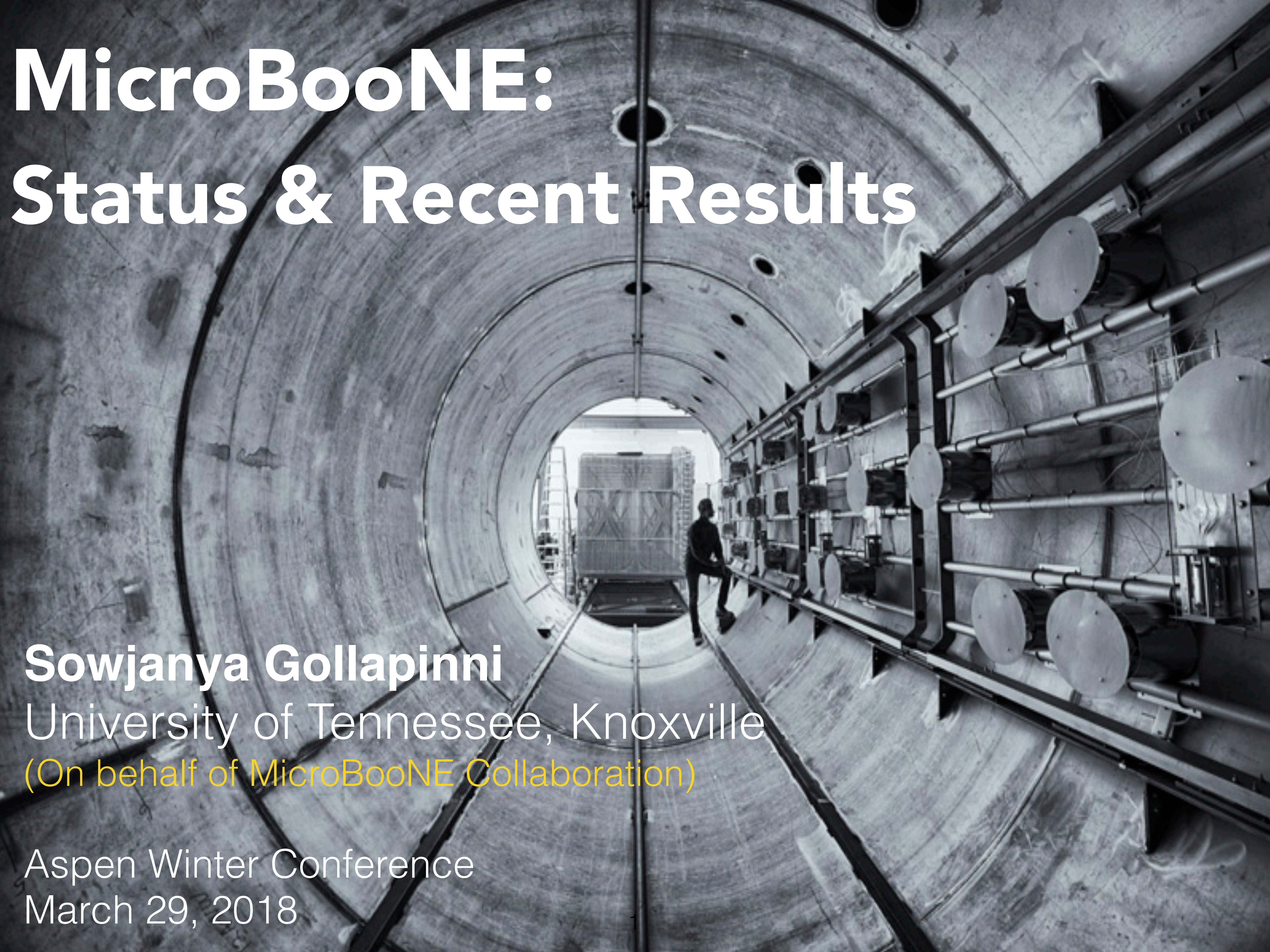


MicroBooNE: Status & Recent Results

Sowjanya Gollapinni
University of Tennessee, Knoxville
(On behalf of MicroBooNE Collaboration)

Aspen Winter Conference
March 29, 2018

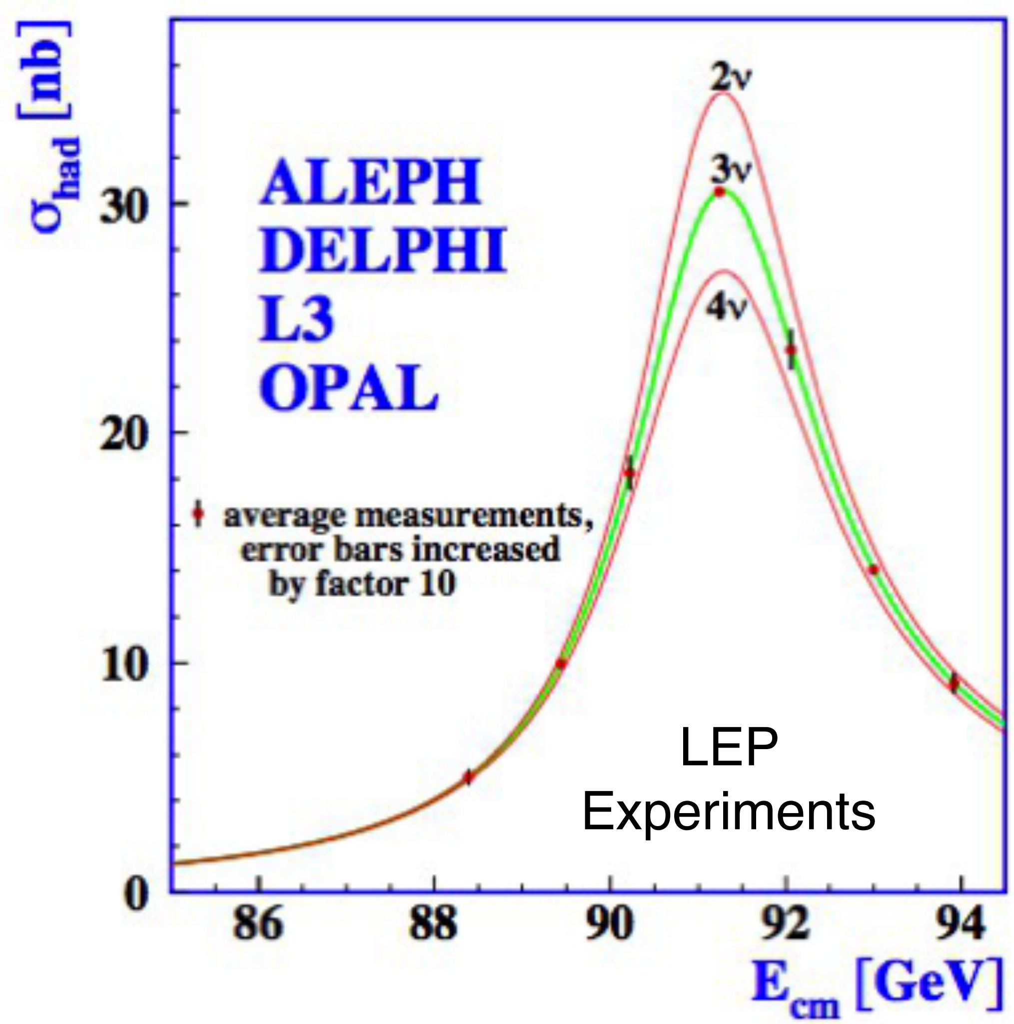
3-flavor Neutrino Oscillations: A well established phenomena

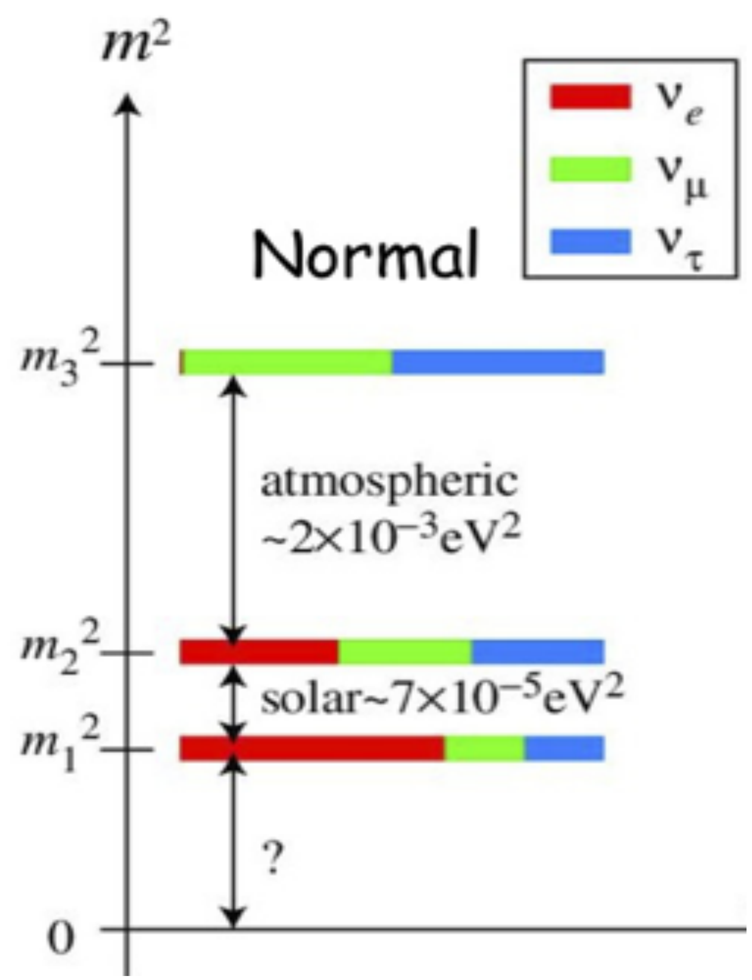
We have detected oscillations from
- **Atmospheric**
- **Solar**
- **Accelerator**
- **Reactor**

- Neutrinos oscillate and have tiny masses
- They come in 3 flavors in the SM
- Almost all of our results nicely fit the 3 neutrino Oscillation scenario
  - – 2 mass splittings and 3 mixing angles

The measurement of $\theta_{13} \approx 10^0$ opened door to CP violation in the leptonic sector!

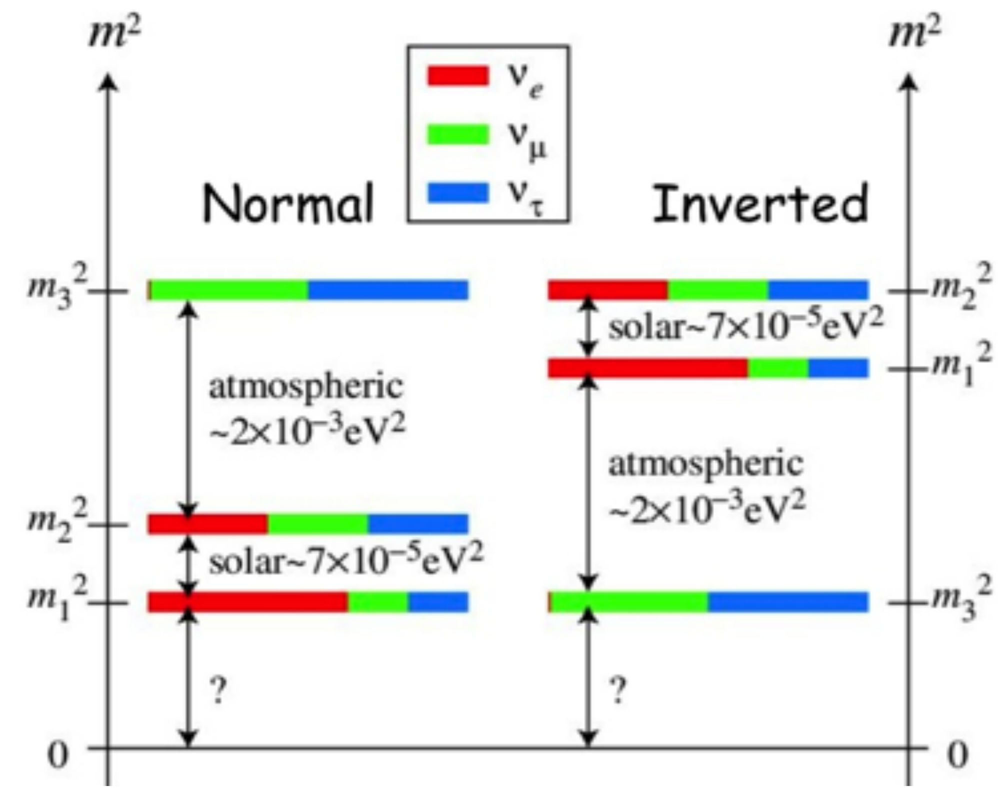
Experimentally confirmed that only three neutrinos couple to the Z boson





Still many profound unknowns

- Are there more than 3 neutrino flavors?
  - — do light sterile neutrinos exist?
- Is CP violated in the leptonic sector?
  - — understanding matter - anti-matter asymmetry?
- What is the Neutrino mass hierarchy?
  - — which neutrino is the lightest?

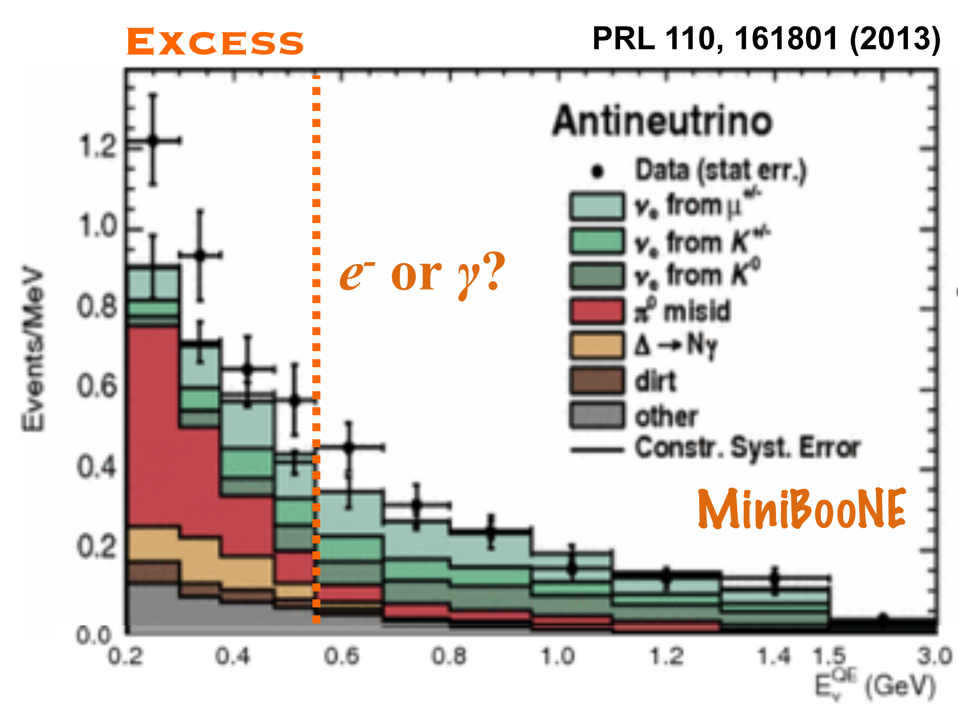


Several anomalies that don't fit in the 3 oscillation scenario: A New Neutrino?

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ

arXiv:1204.5379 (2012)

PRL 110, 161801 (2013)



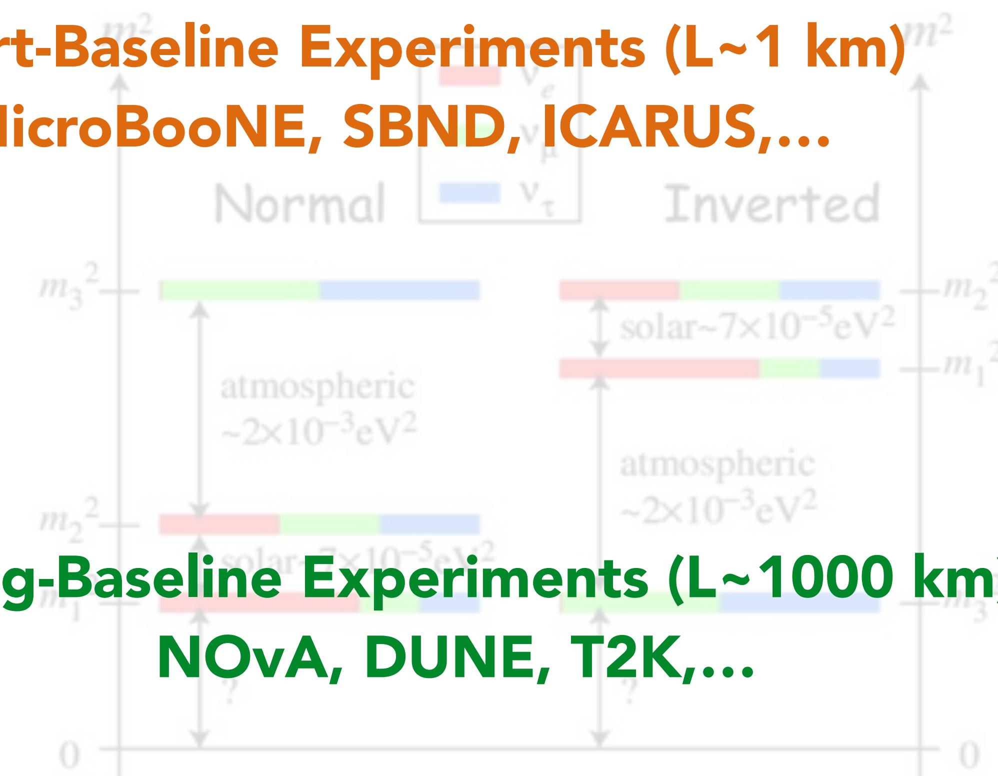
Still many profound unknowns

- Are there more than 3 neutrino flavors?
  — do light sterile neutrinos exist?

Short-Baseline Experiments (L~1 km)
MicroBooNE, SBND, ICARUS,…

- Is CP violated in the leptonic sector?
  — understanding matter - anti-matter asymmetry?
- What is the Neutrino mass hierarchy?
  — which neutrino is the lightest?

Long-Baseline Experiments (L~1000 km)
NOvA, DUNE, T2K,…



Several anomalies that don't fit
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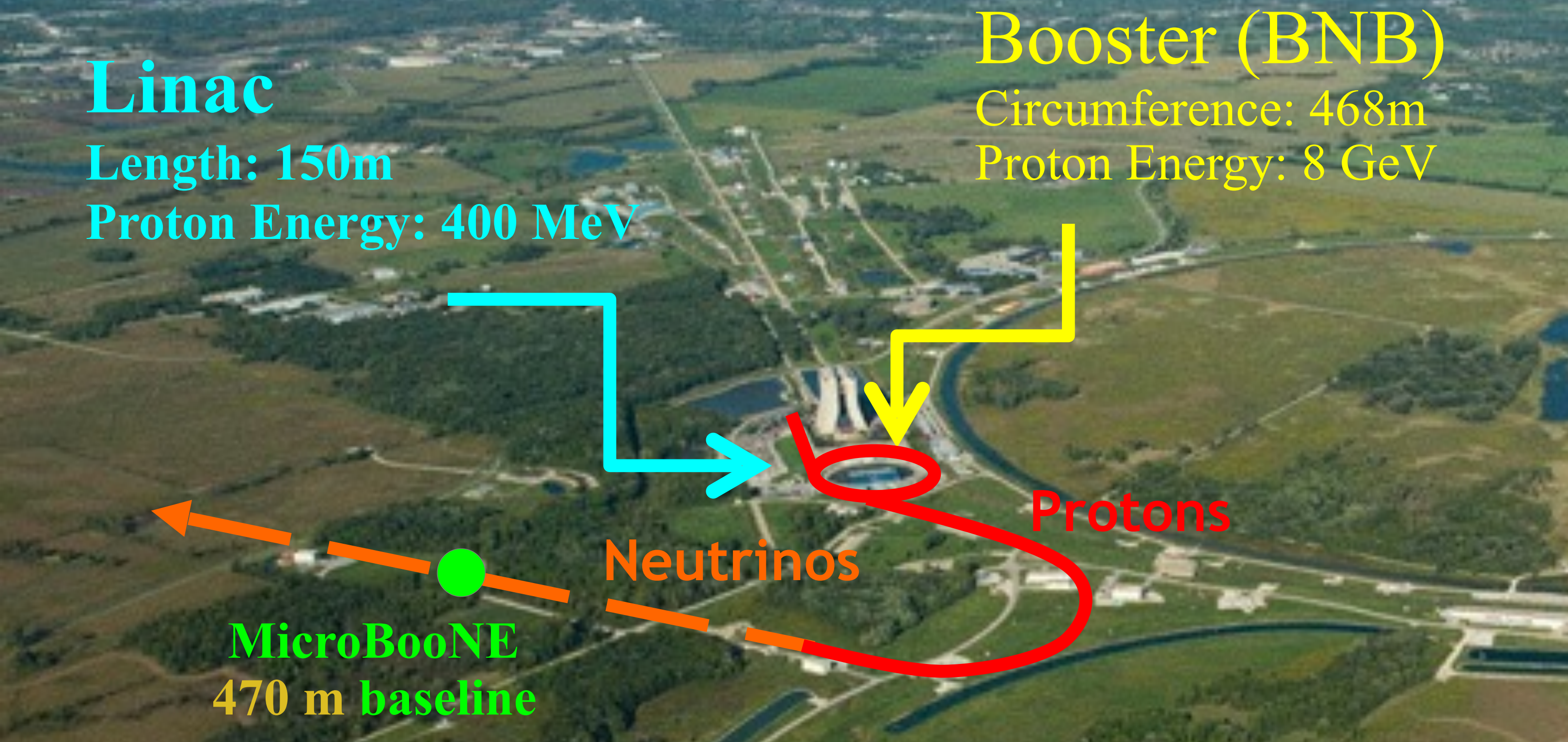
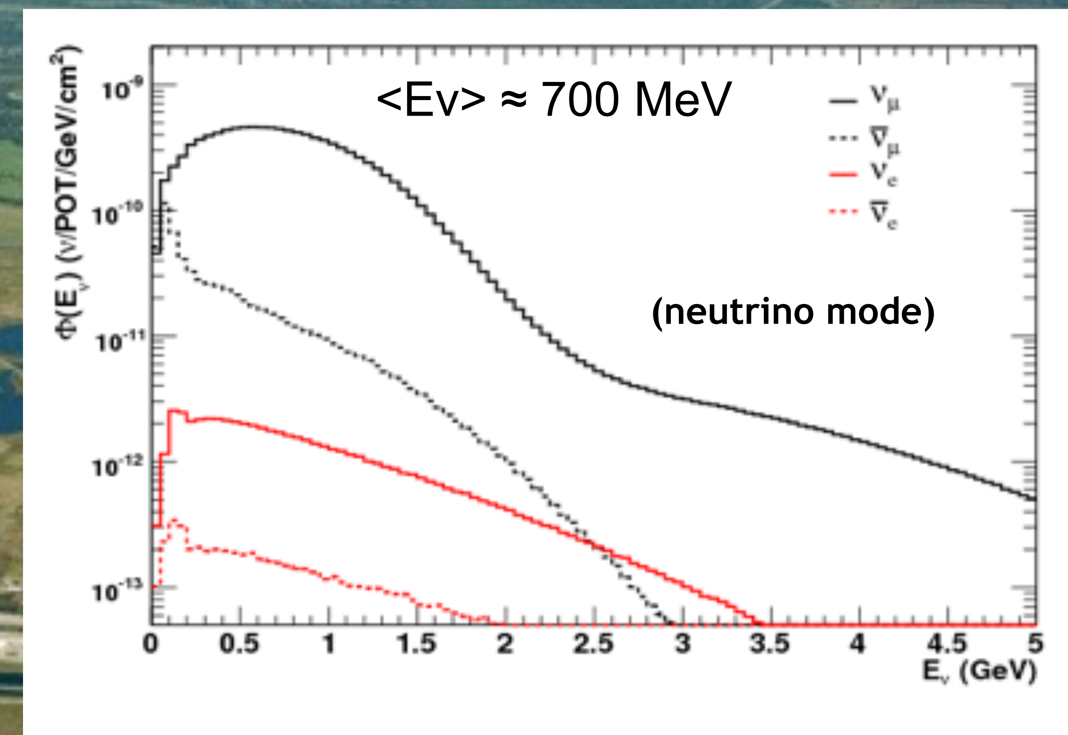
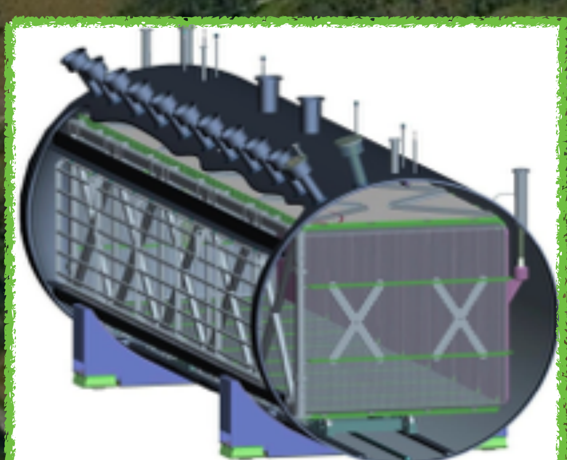
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

arXiv:1204.5379 (2012)

The MicroBooNE Experiment



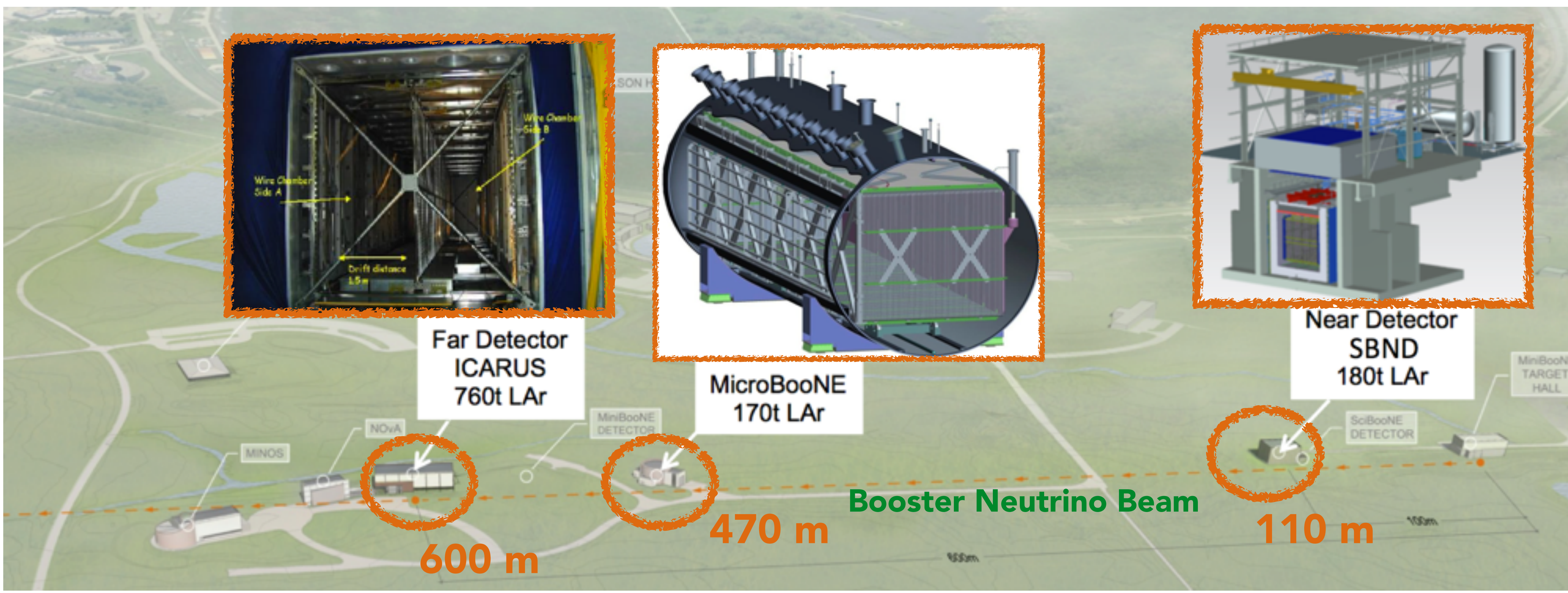




- Short-Baseline Oscillation Experiment
- Located on the Booster Neutrino Beam (BNB) at Fermilab

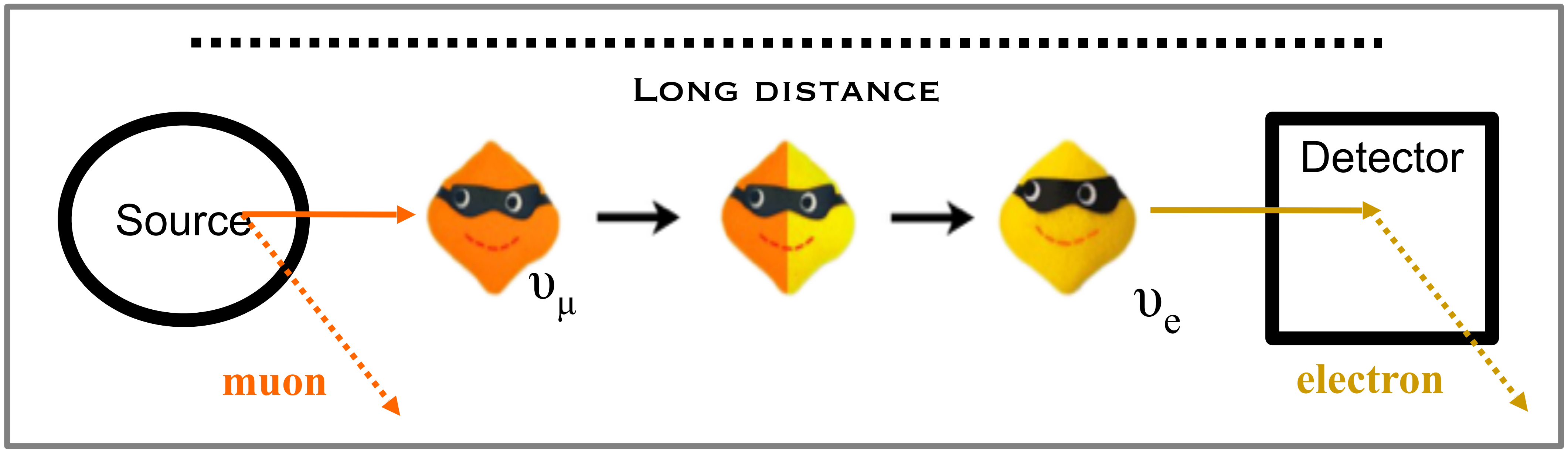
The Short-Baseline Neutrino Program

- MicroBooNE is paving way for the three-detector SBN program to more definitively address the sterile neutrino question where we have existing hints
  - Well understood BNB beam
  - Same detector technologies, same beam = reduced systematics!



υ_e Appearance Signal

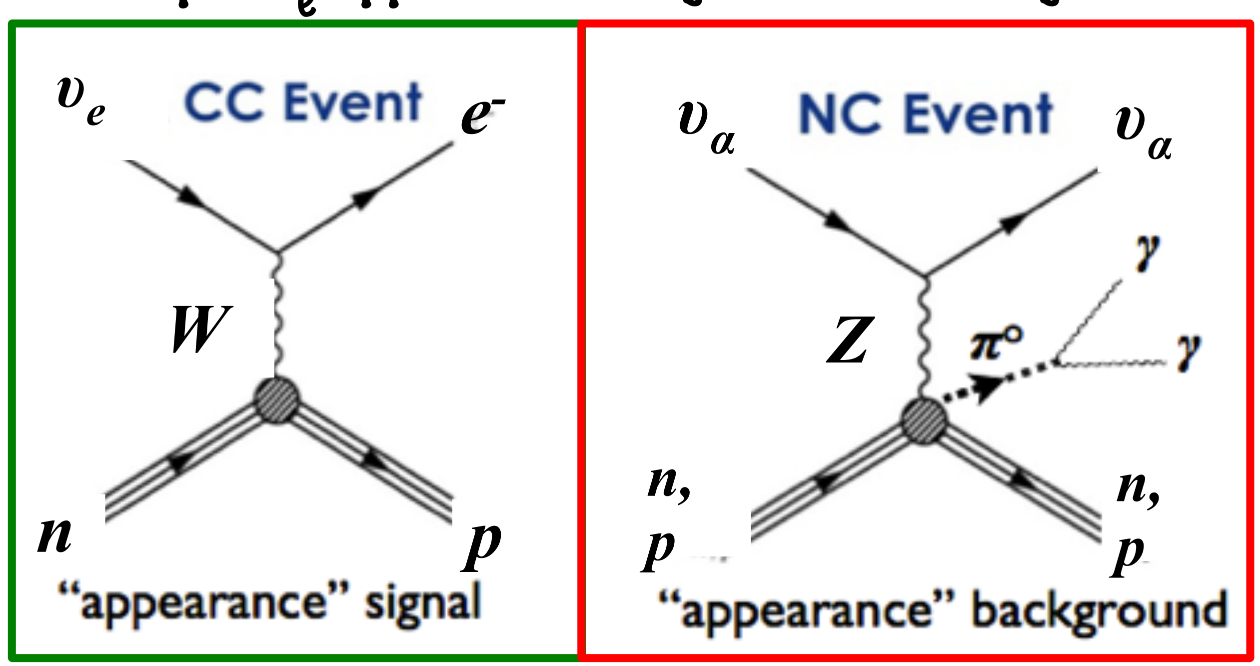
(look for excess of ν_e events)



cannot measure the neutrino flavor directly, only through the outgoing lepton

Example υ_e appearance signal and background

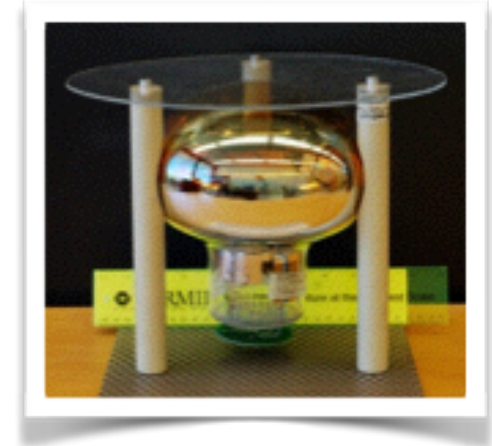
- Charged-current events typically signal events
- Can use out-going lepton to tag neutrino flavor



- Neutral-current events typically background events
- no way to tag the neutrino flavor

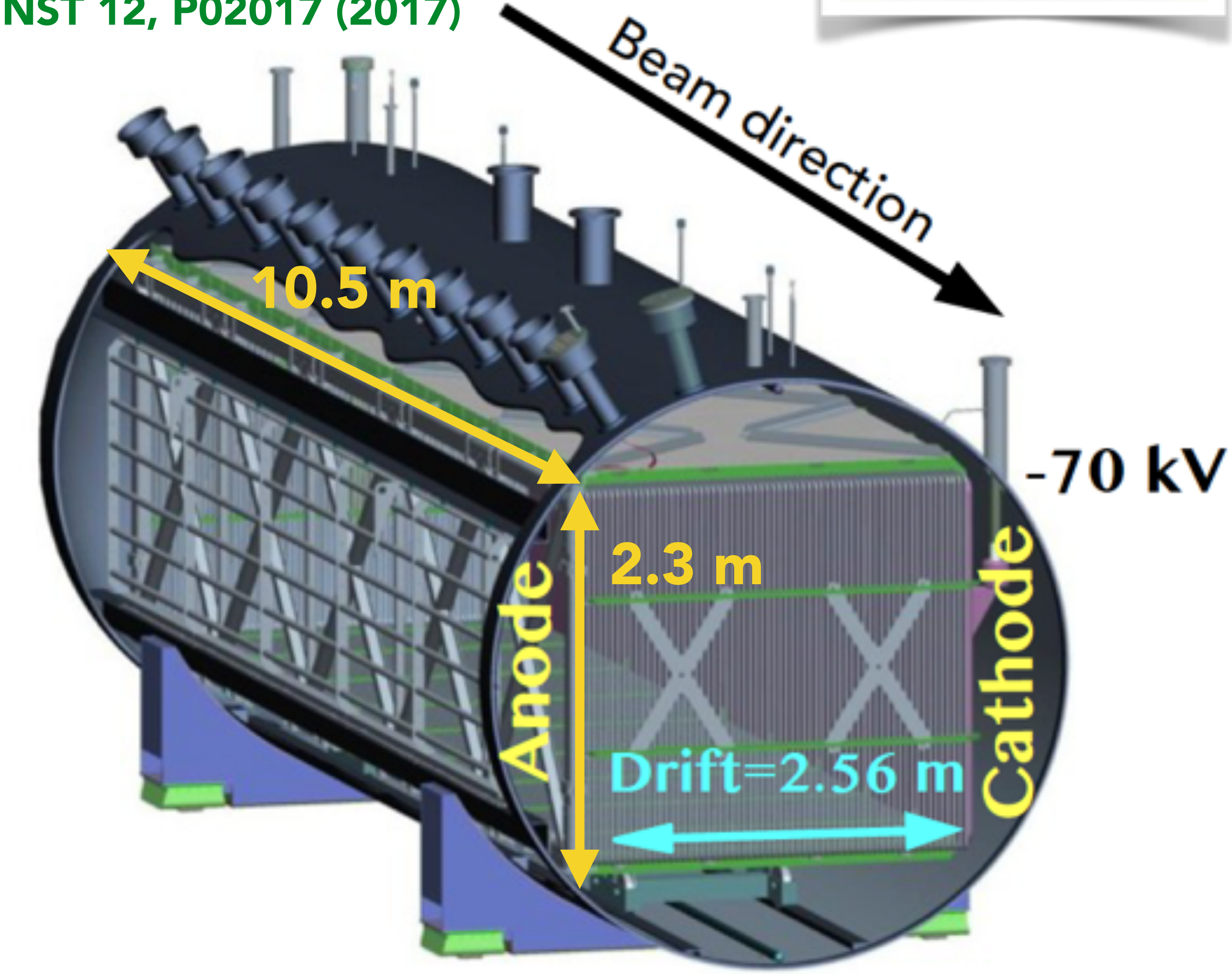
e/γ separation crucial for υ_e appearance experiments!

The MicroBooNE LArTPC



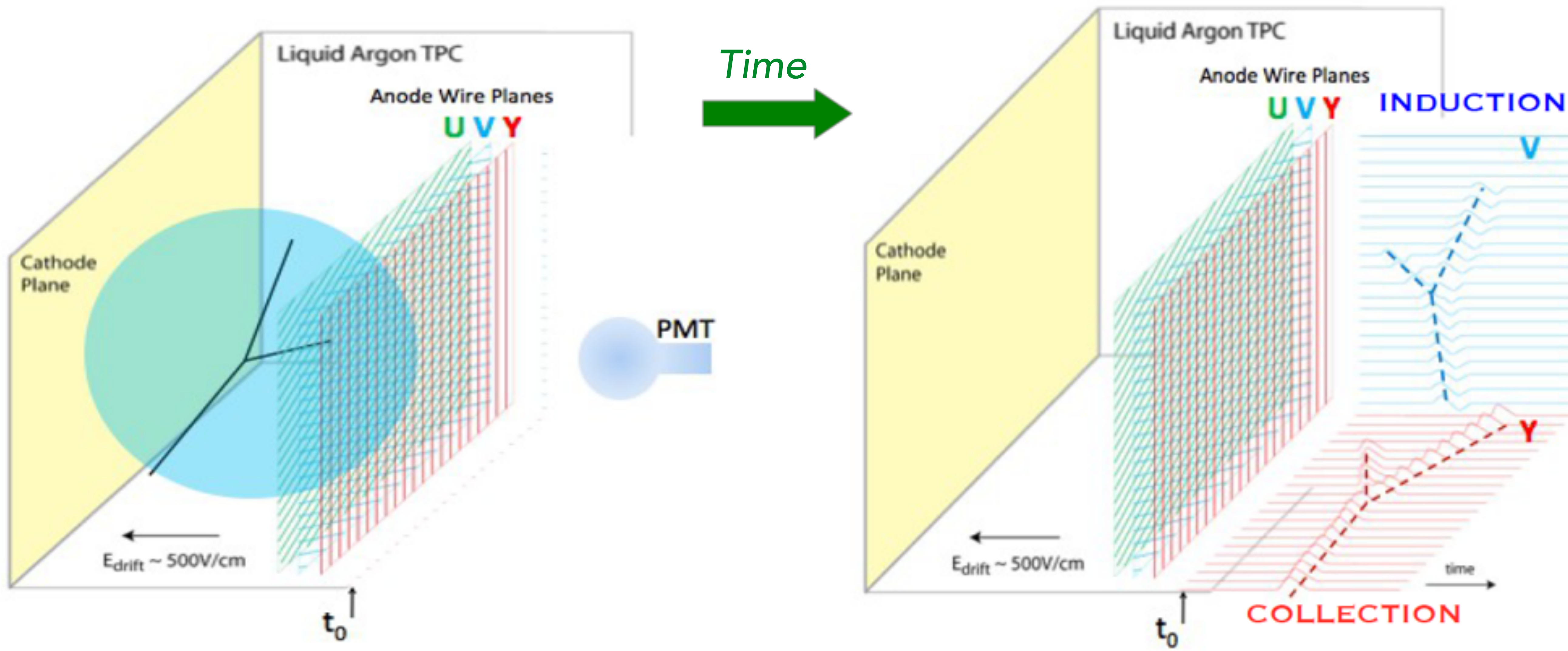
- **LArTPC = Liquid Argon Time Projection Chamber**
- Surface-based, 89-ton active volume liquid argon
- One drift chamber
  - Cathode at -70kV
  - Drift at 2.56 m
  - E-field at 273 V/cm
- Three wire planes
  - 2 induction, 1 collection
  - 3 mm wire pitch
  - 3 mm wire plane spacing
- PMT and UV Laser System
- Collecting cosmic and neutrino data since Fall 2015

JINST 12, P02017 (2017)



E = 273 V/cm

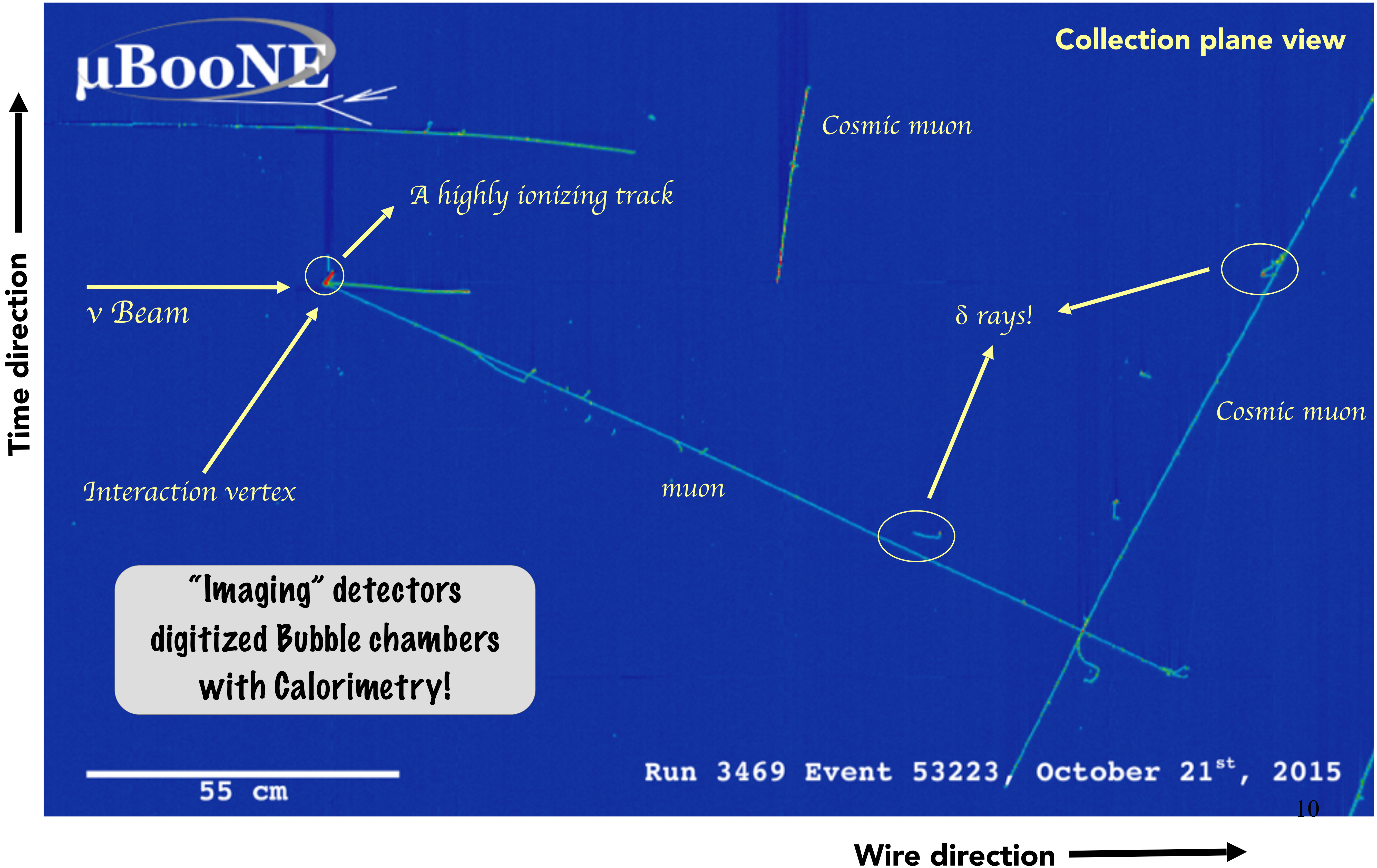
The LArTPC Principle



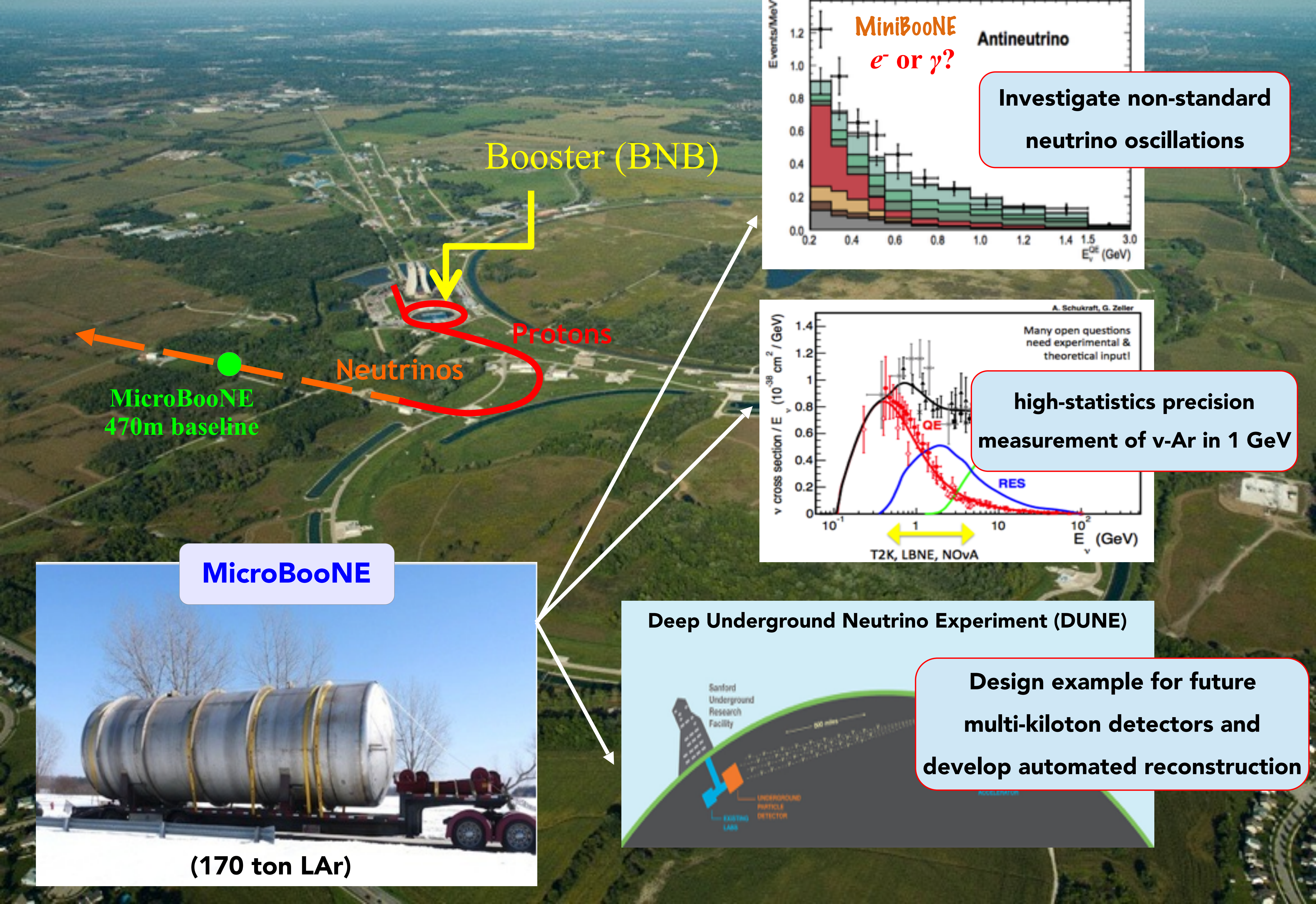
- Argon makes a desirable target (dense, abundant,…)
- Two signals: Ionization signal & Scintillation light
- Finely (mm-scale) segmented anode wires — excellent resolution!
- Bubble chamber quality images in HD!
- Technology allows for scalability — can build massive detectors

Wire Planes + Signal Arrival Time = 3D Image

A neutrino event in MicroBooNE LArTPC

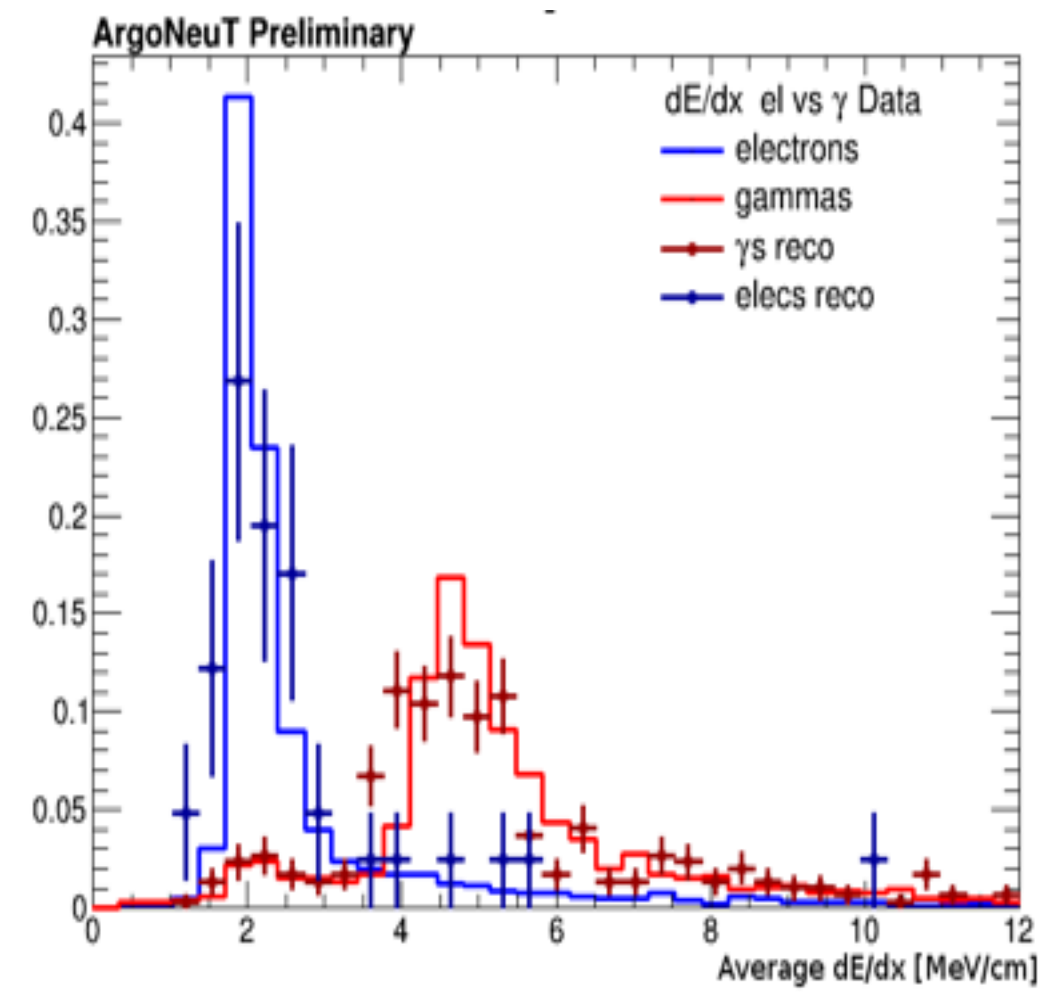


MicroBooNE Goals

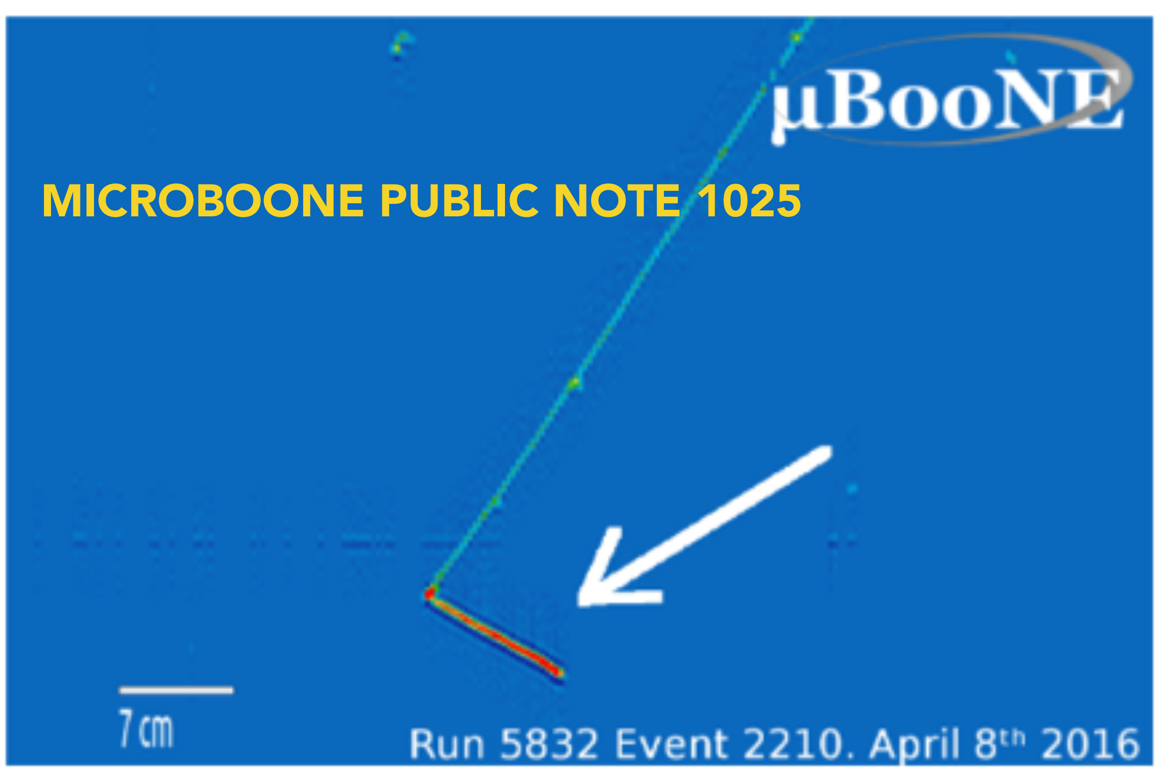


High Resolution Detector

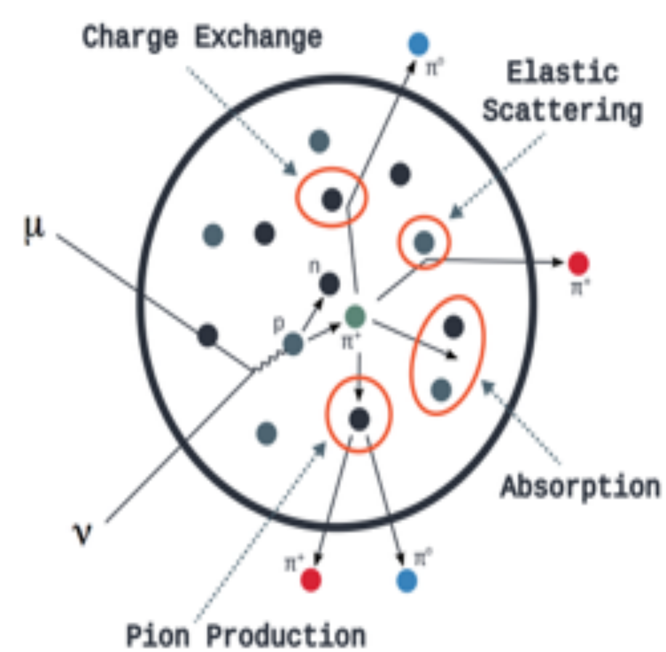
- **e/γ shower separation**: via both event topology and early dE/dx
- **Neutrino energy reconstruction, hadron kinematics come into play**
  - Fine grained tracking
  - event classification in terms of final state topology
  - Ability to reconstruct hadrons



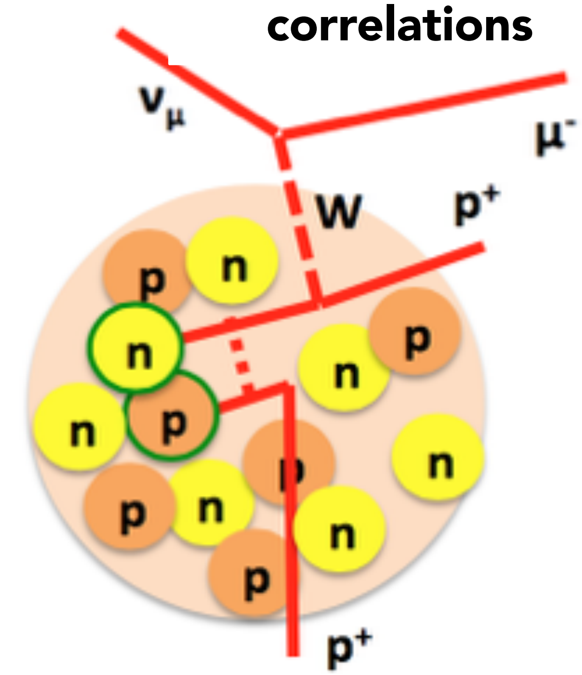
Automated Proton Track Identification



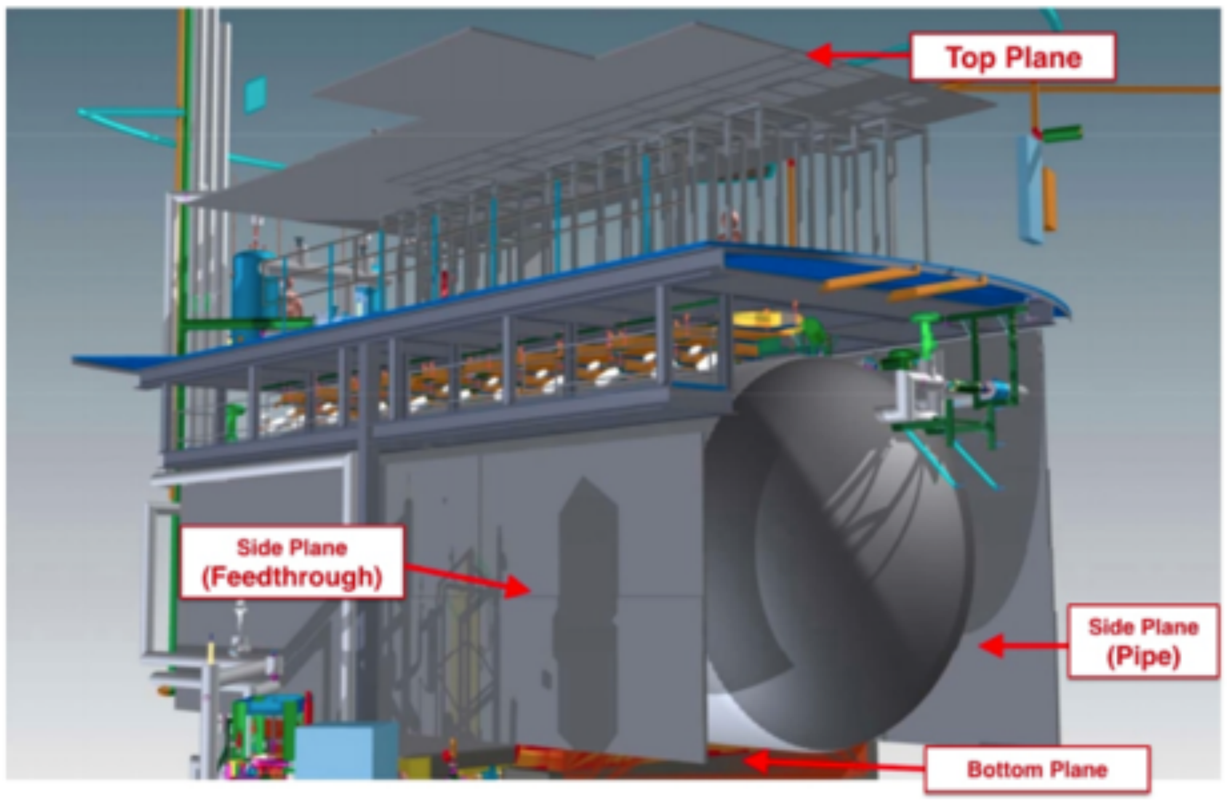
Final state Interactions

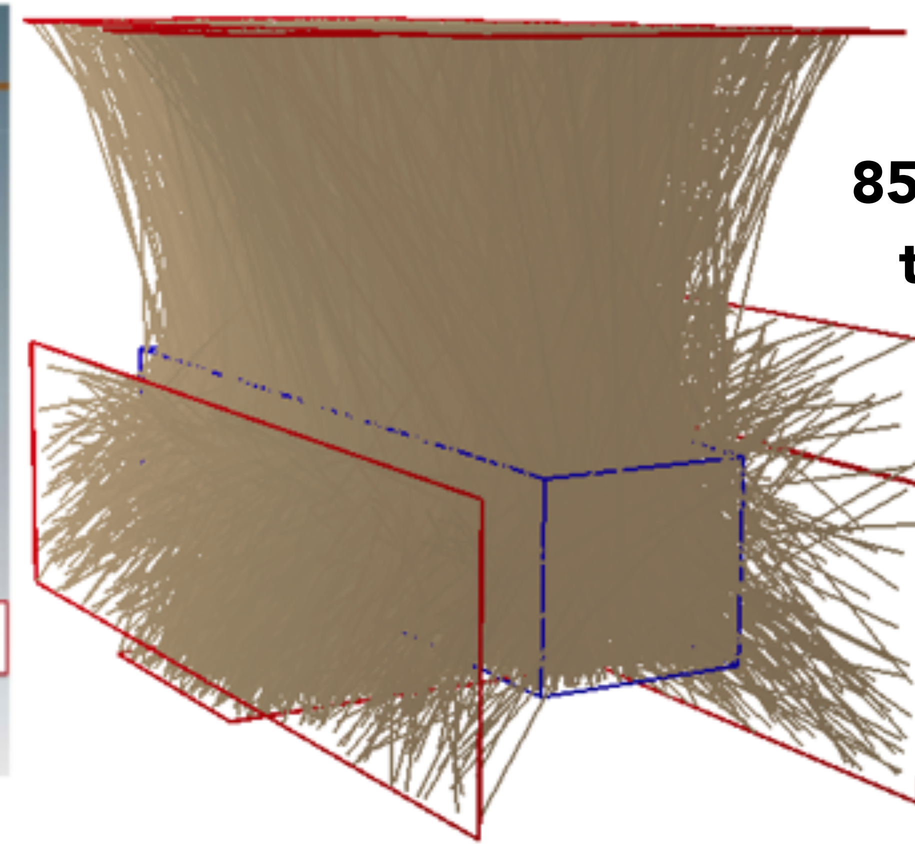


Nucleon-nucleon correlations



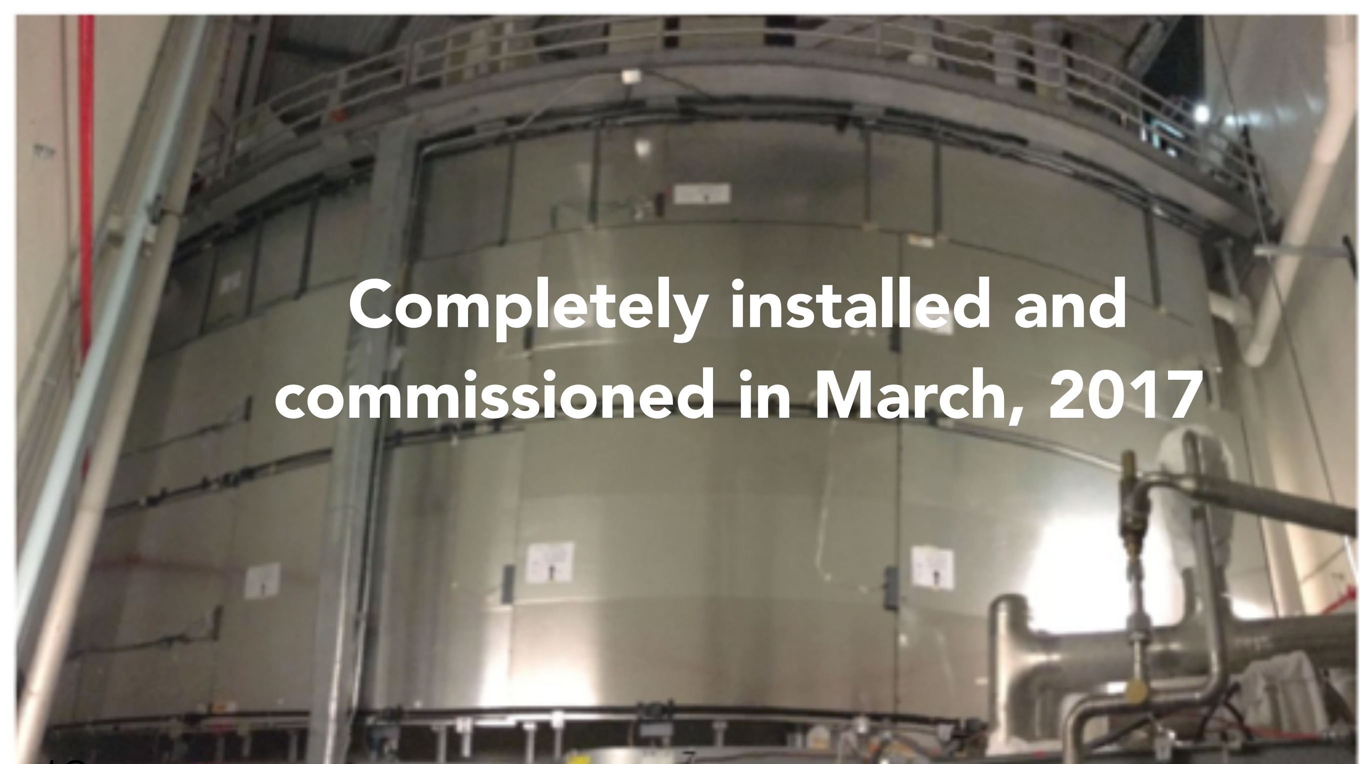
Upgrades: Cosmic Ray Tagger System



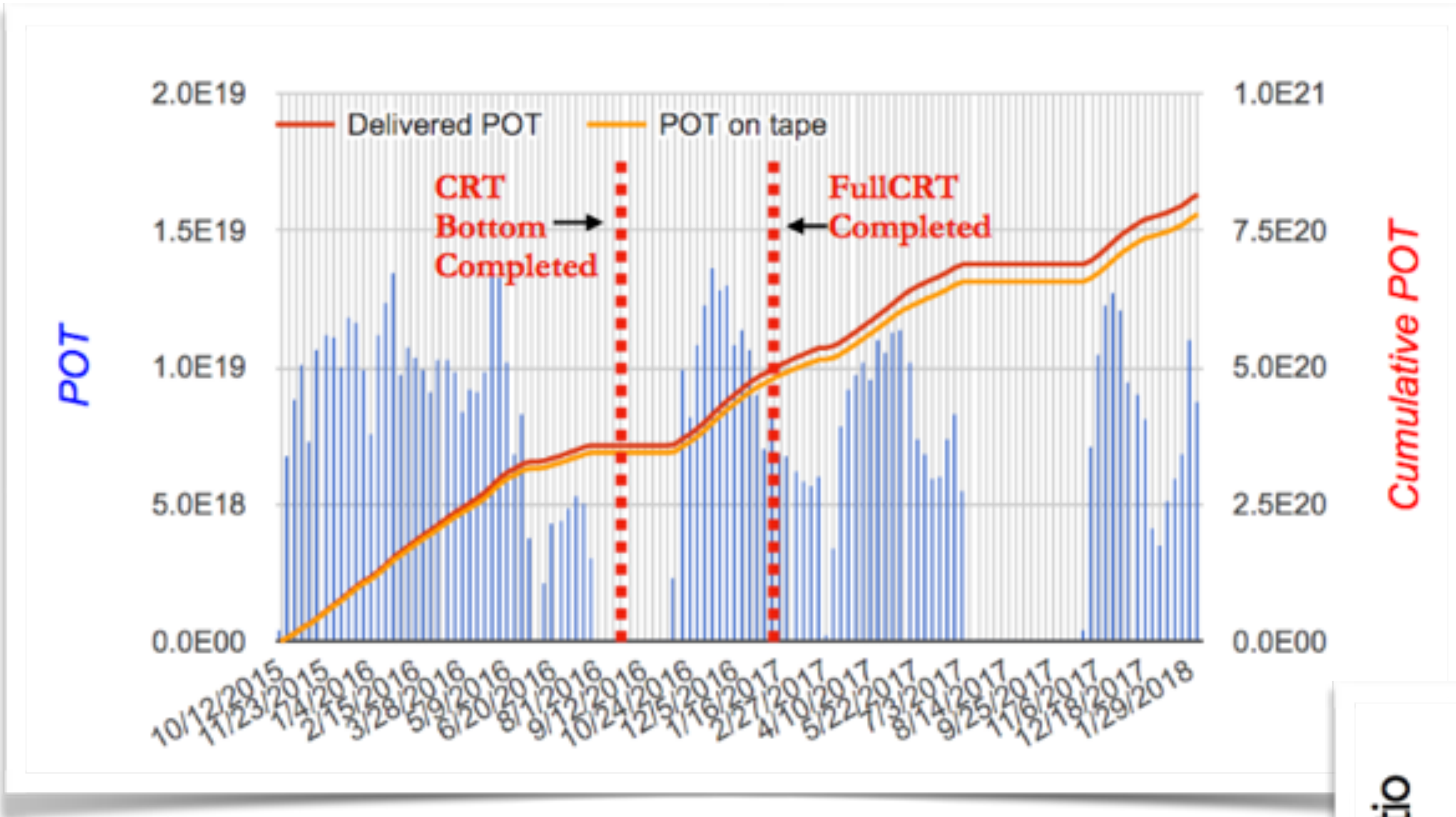


85% coverage for through-going muons

- Plastic Scintillator Modules & SiPM readout
- Design & Construction paper under preparation for JINST
- Currently developing matching techniques between TPC and CRT

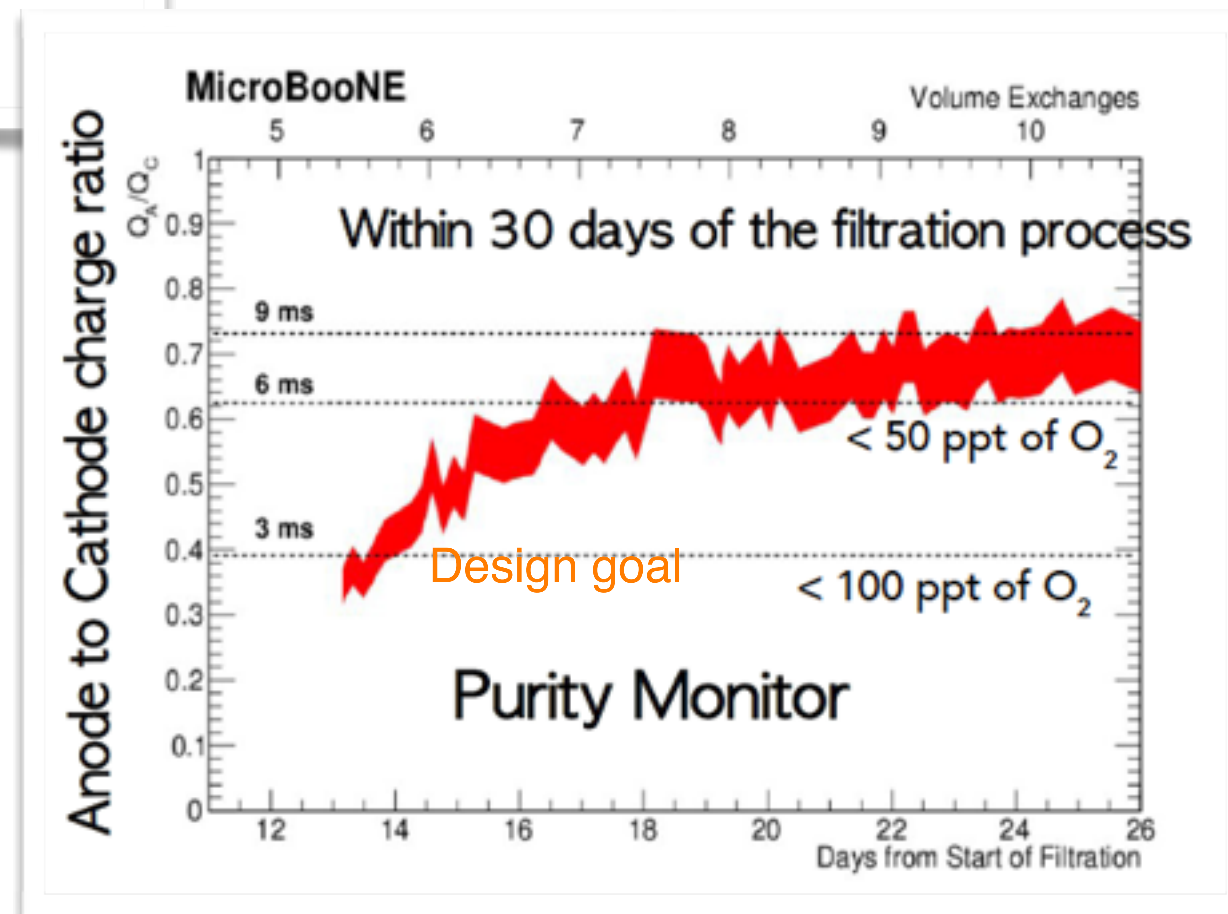


MicroBooNE Operations



- TPC running stably since October 2015
- 97% beam uptime with full CRT since March 2017
- Accumulated more than 7.5E20 POT BNB data, 2.5E20 POT with CRT.

- *Argon purity critical for LArTPC operation*
- Electro-negative impurities (O_2 and H_2O) in argon can absorb drifting electrons
- Achieved 3 times the design goal for purity within 30 days of operation!



MICROBOONE PUBLIC NOTE 1003

MicroBooNE Publications & Public Notes

7 Publications,19 public notes
(8 more in the pipeline)

Public Notes

Date	Note	Title
08/30/17	MICROBOONE-NOTE-1026-PUB	A Measurement of the Attenuation of Drifting Electrons in the MicroBooNE LArTPC
07/22/17	MICROBOONE-NOTE-1028-PUB	Establishing a Pure Sample of Side-Piercing Through-Going Cosmic-Ray Muons for LArTPC Calibration in MicroBooNE
06/04/17	MICROBOONE-NOTE-1024-PUB	Measurement of Reconstructed Charged Particle Multiplicities of Neutrino Interactions in MicroBooNE
01/26/17	MICROBOONE-NOTE-1025-PUB	Proton Track Identication in MicroBooNE Simulation for Neutral Current Elastic Events
11/29/16	MICROBOONE-NOTE-1018-PUB	Study of Space C
07/04/16	MICROBOONE-NOTE-1017-PUB	A Method to Extr the TPC Wire Pla
07/04/16	MICROBOONE-NOTE-1016-PUB	Noise Characteri TPC
07/04/16	MICROBOONE-NOTE-1015-PUB	The Pandora mul pattern recogniti
07/04/16	MICROBOONE-NOTE-1014-PUB	A Comparison of from MicroBooNI
07/04/16	MICROBOONE-NOTE-1013-PUB	MicroBooNE Det
07/04/16	MICROBOONE-NOTE-1012-PUB	Demonstration o MicroBooNE Dat
07/04/16	MICROBOONE-NOTE-1010-PUB	Selection and kir current inclusive data
07/01/16	MICROBOONE-NOTE-1008-PUB	Michel Electron F LArTPC Cosmic Data
05/03/16	MICROBOONE-NOTE-1006-PUB	Study Towards an Event Selection for Neutral Current Inclusive Single Pi0 Production in MicroBooNE
05/30/16	MICROBOONE-NOTE-1005-PUB	Cosmic Shielding Studies at MicroBooNE
11/06/15	MICROBOONE-NOTE-1004-PUB	MC performance study for an early numu charged-current inclusive analysis with MicroBooNE
05/29/16	MICROBOONE-NOTE-1003-PUB	Measurement of the Electronegative Contaminants and Drift Electron Lifetime in the MicroBooNE Experiment
11/02/15	MICROBOONE-NOTE-1002-PUB	First neutrino interactions observed with the MicroBooNE Liquid-Argon TPC detector
08/28/15	MICROBOONE-NOTE-1001-TECH	Noise Dependence on Temperature and LAr Fill Level in the MicroBooNE Time Projection Chamber

Publications/Documents by the MicroBooNE Collaboration

- MicroBooNE collaboration, "Ionization Electron Signal Processing in Single Phase LAr TPCs I: Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation", arXiv:1802.08709, submitted to JINST
- 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, Eur. Phys. J. C78, 1, 82 (2018)
- MicroBooNE collaboration, "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)
- MicroBooNE collaboration, "Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC", arXiv:1705.07341, JINST 12, P08003 (2017), Fermilab News article (07/05/17)
- 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, JINST 12 P10010 (2017)
- 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)

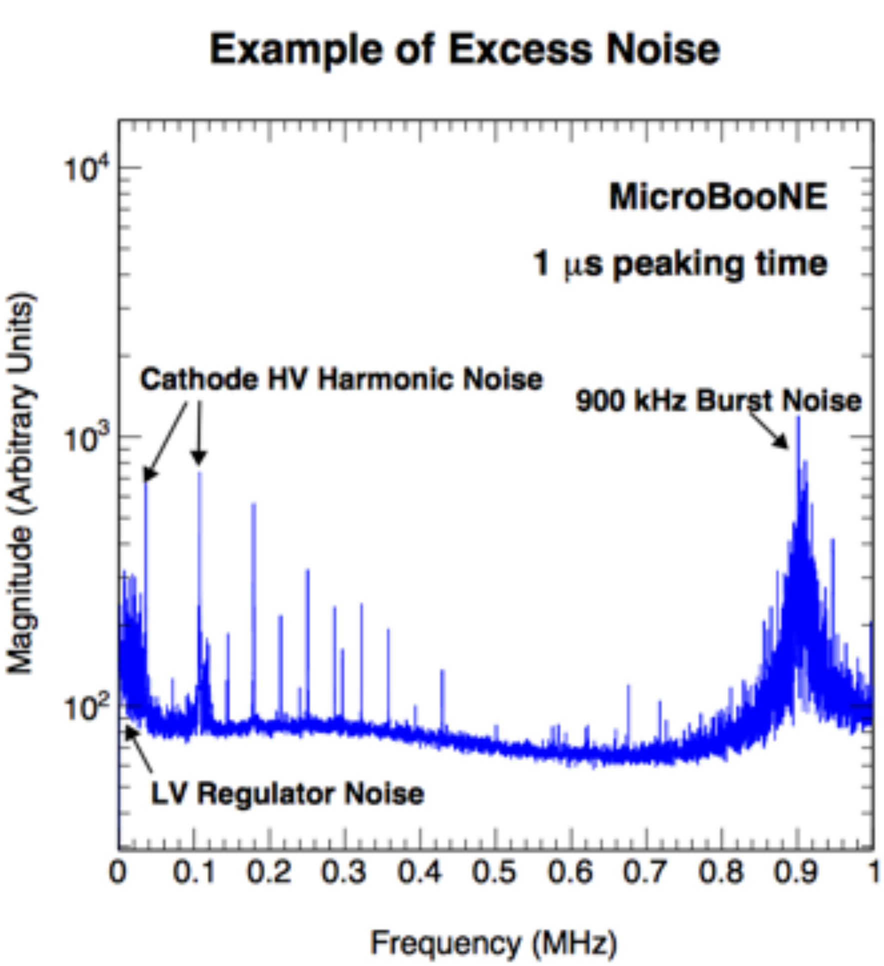
Papers in all categories

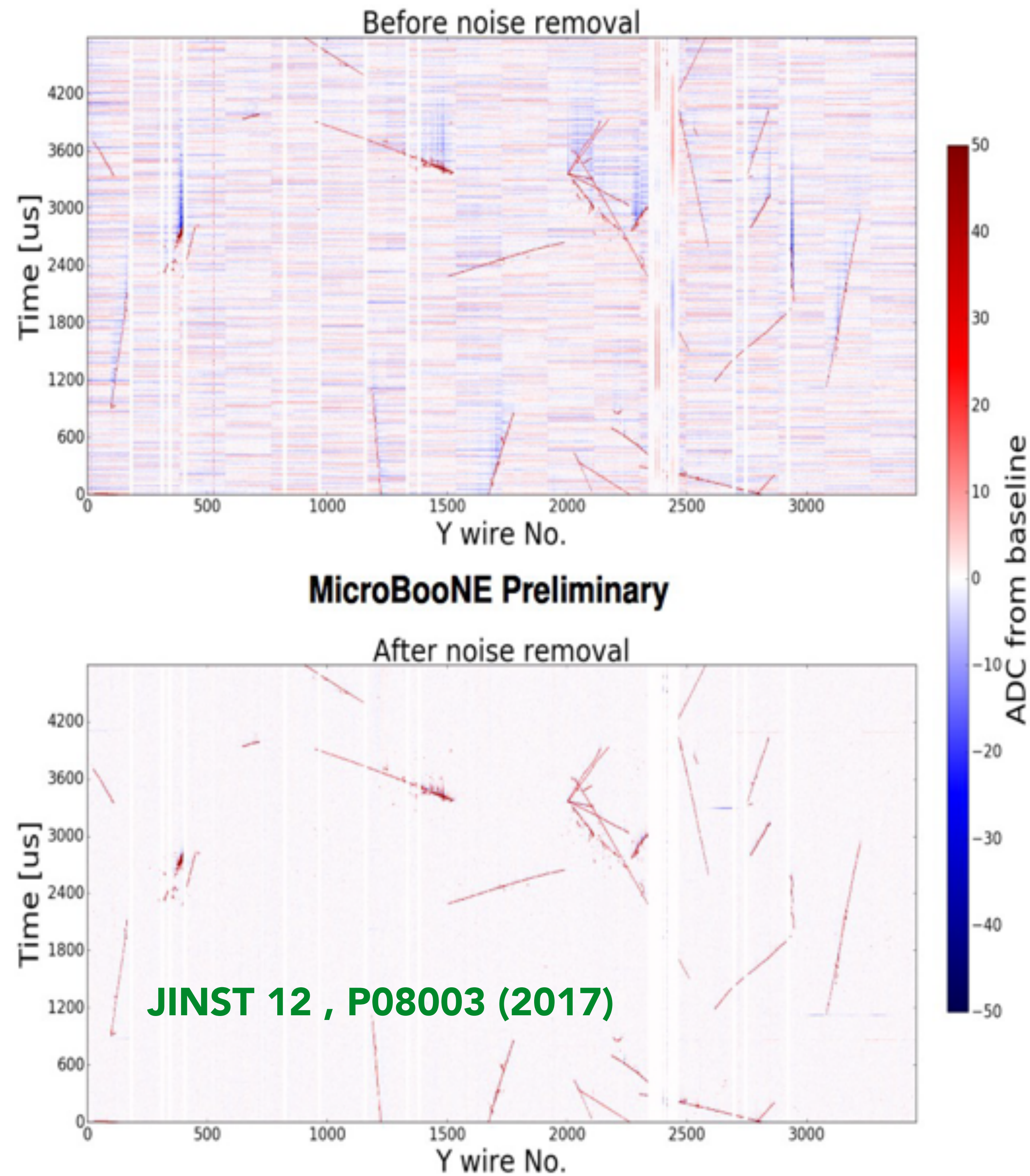
- *Construction & Operation*
- *Detector Physics*
- *Reconstruction Techniques*
- *Towards Cross-section Measurements*
- *Towards Oscillation Measurements*

TPC Noise Filtering

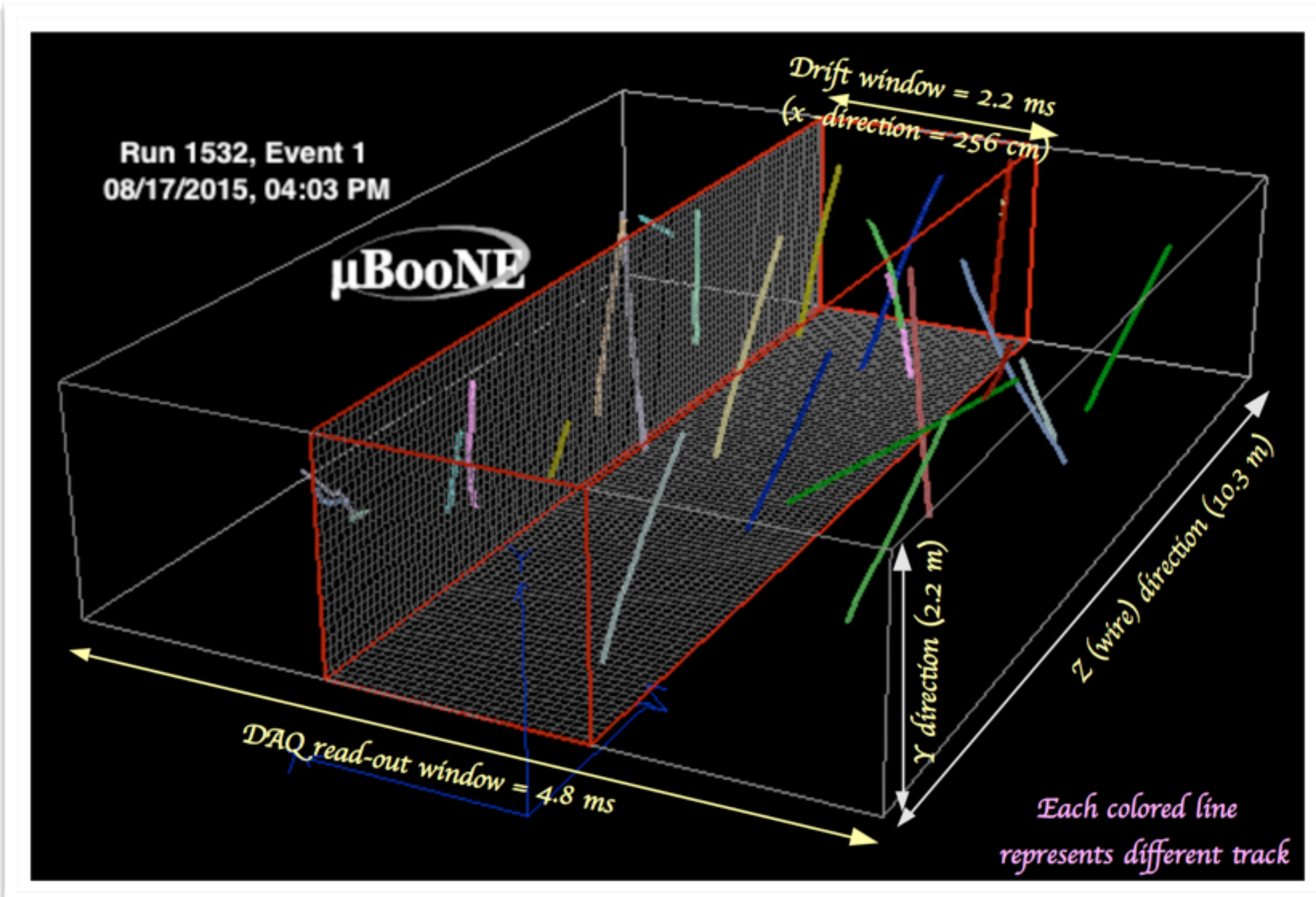
- Several noise sources were identified and mitigated: *both Hardware upgrades & Noise filtering techniques*
- Peak Signal-to-Noise Ratio
  - *> 16 (induction planes)*
  - *> 35 (collection plane)*

Significantly lower noise levels achieved in a 100-ton scale LArTPC





Fully Automated Track Reconstruction

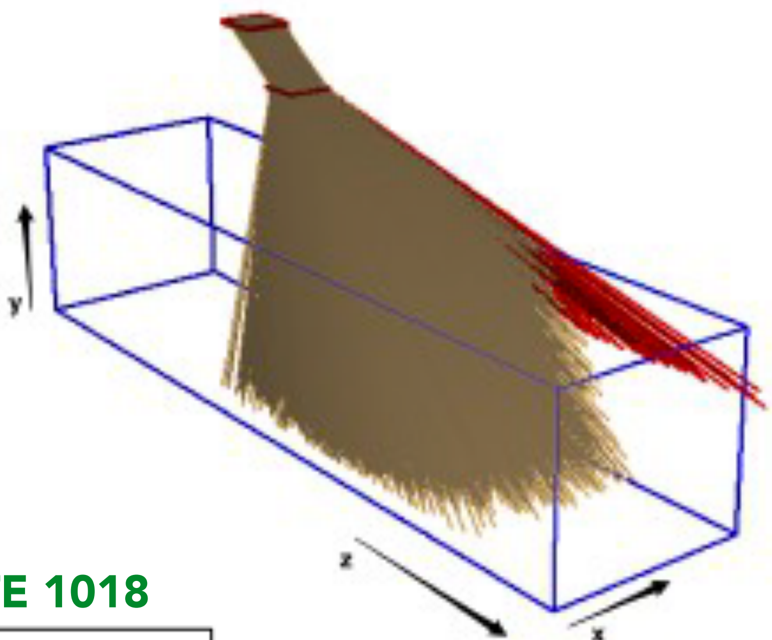


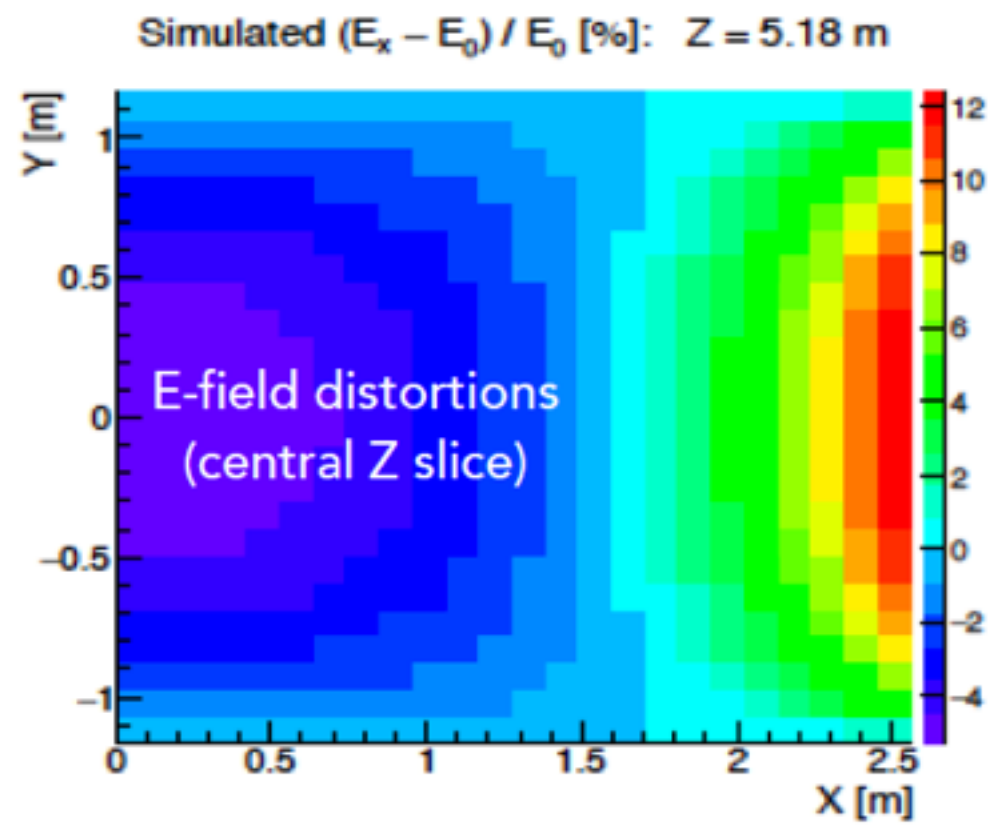
- **Surface location = multiple cosmic tracks**
- **Developing and Testing our reconstruction & calibration on Cosmics**

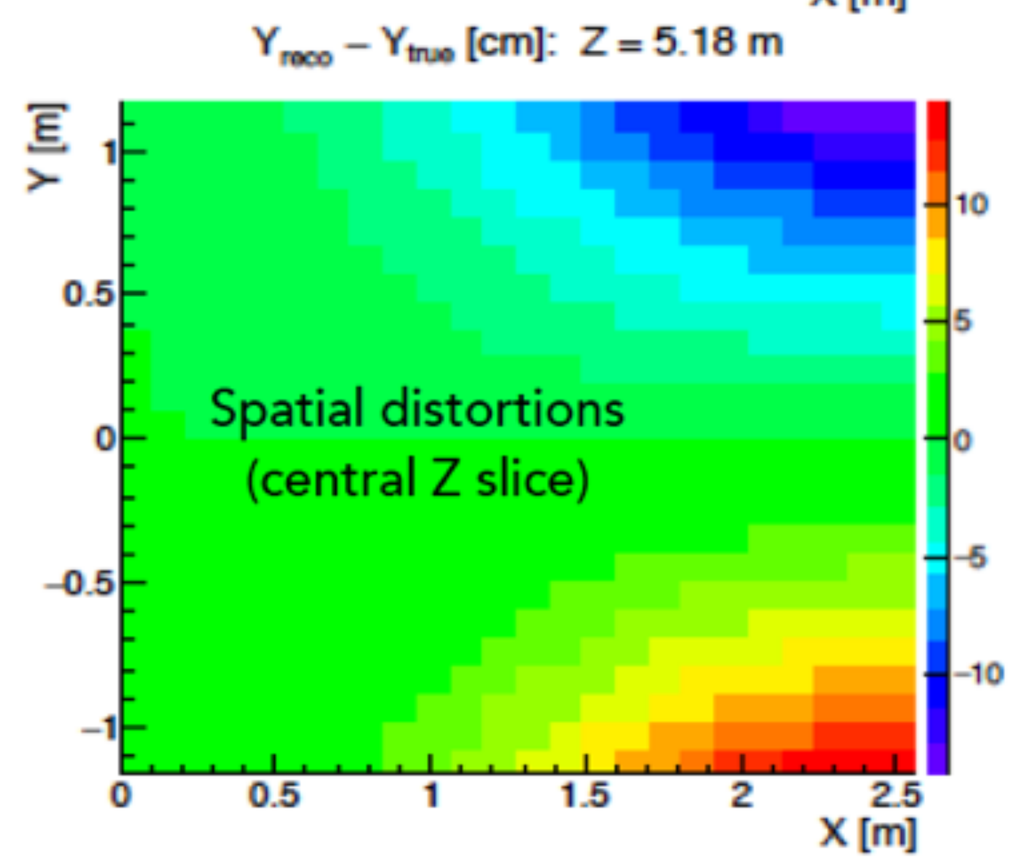
Space charge Effects

- Build up of slow moving Ar+ ions in the detector due to e.g. cosmic rays results in
  - *5 to 12% variation (drift) in E-field w.r.t. nominal*
  - *5 cm (drift) and 12 to 15 cm (non-drift) spatial variation*

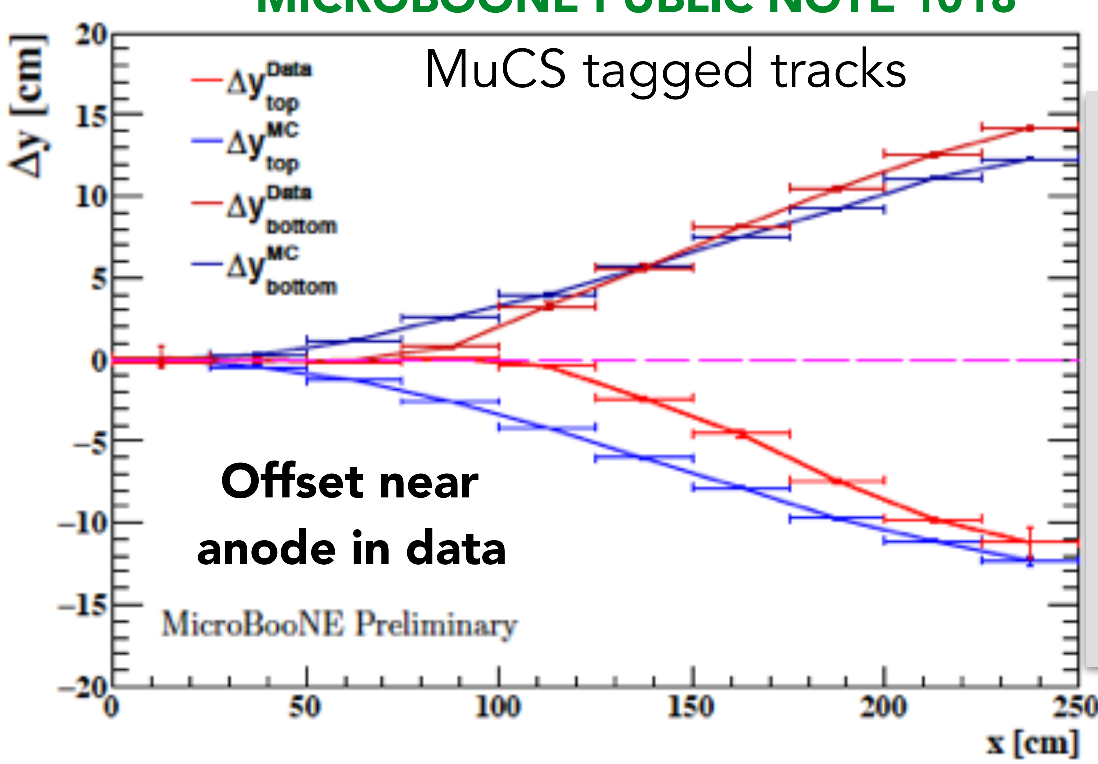
First Measurement using tracks from a small **Muon Counter System (MuCS)** — limited angular coverage







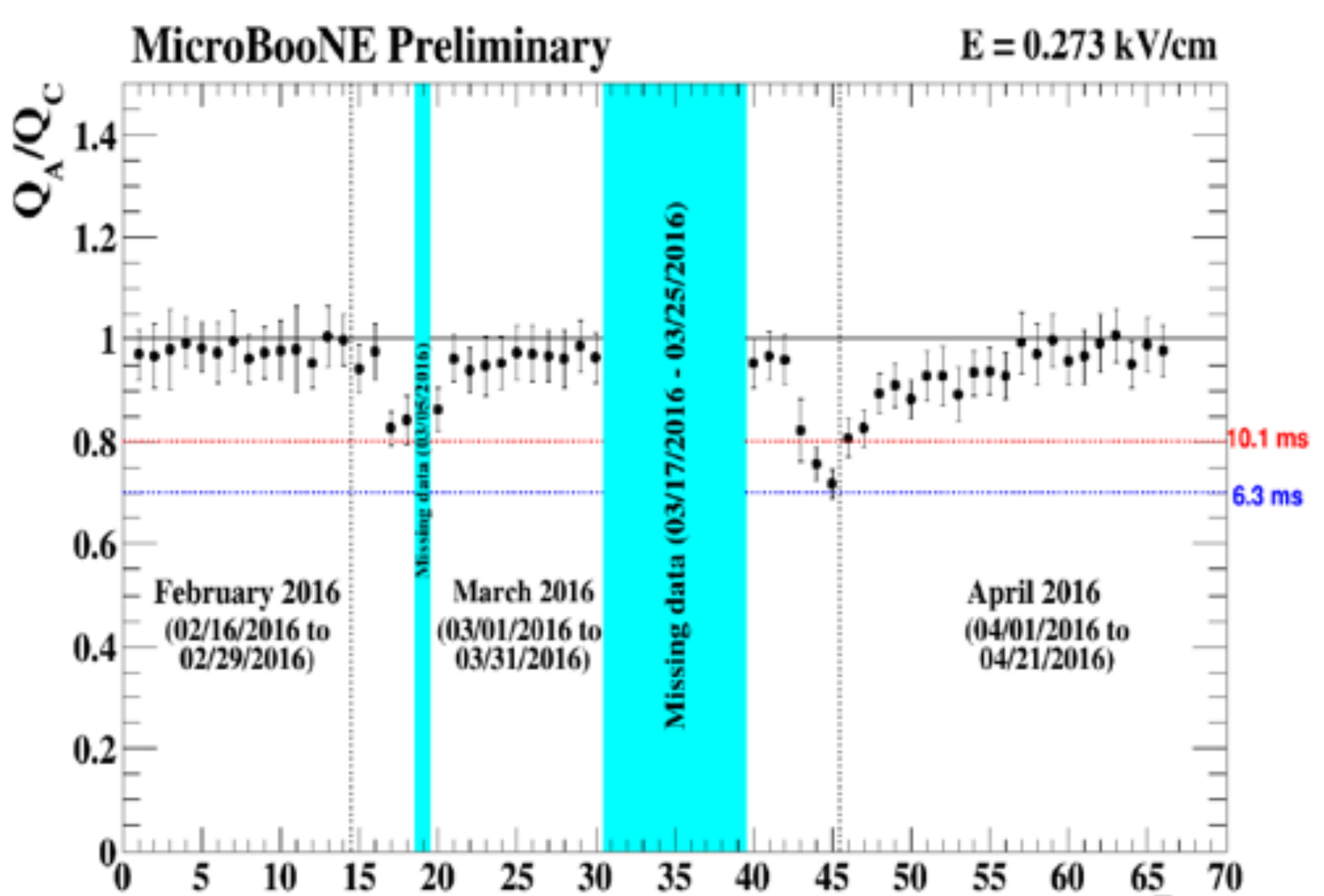
MICROBOONE PUBLIC NOTE 1018



- Data and MC reasonably agree in basic shape and normalization
- Measurements for the full TPC volume planned with laser & larger CRT

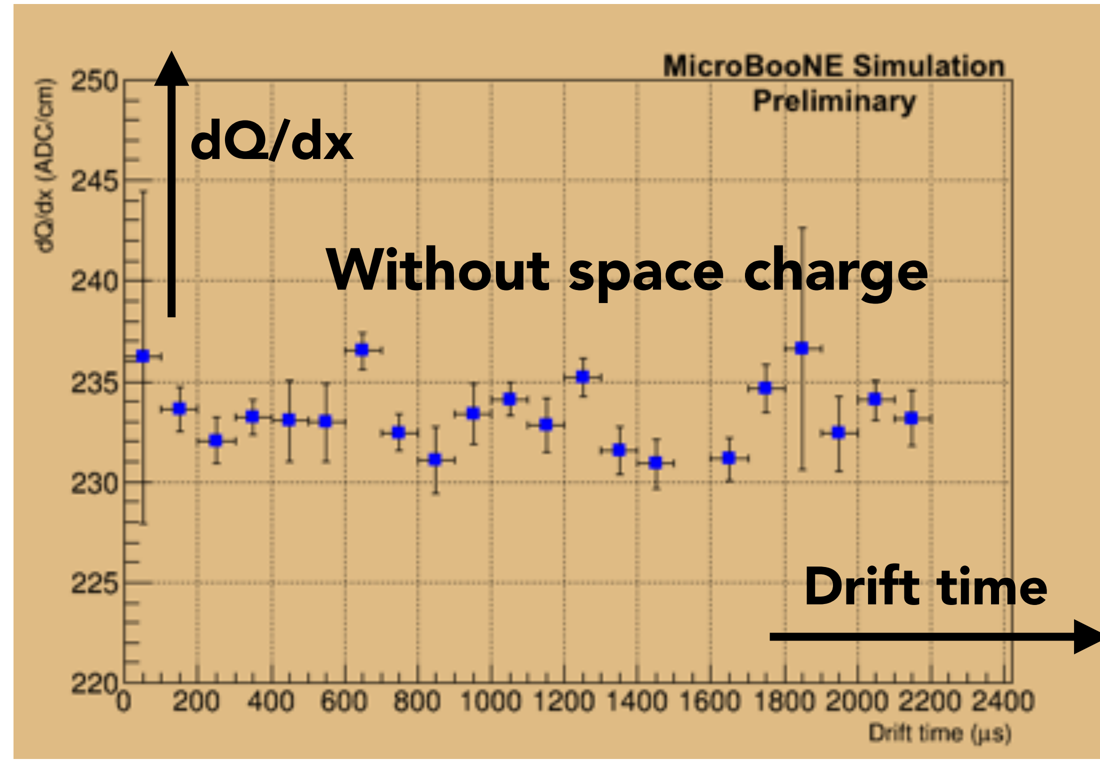
Electron Drift-lifetime & Argon purity

Measurement done using Anode-Cathode crossing *Cosmic muons* from data

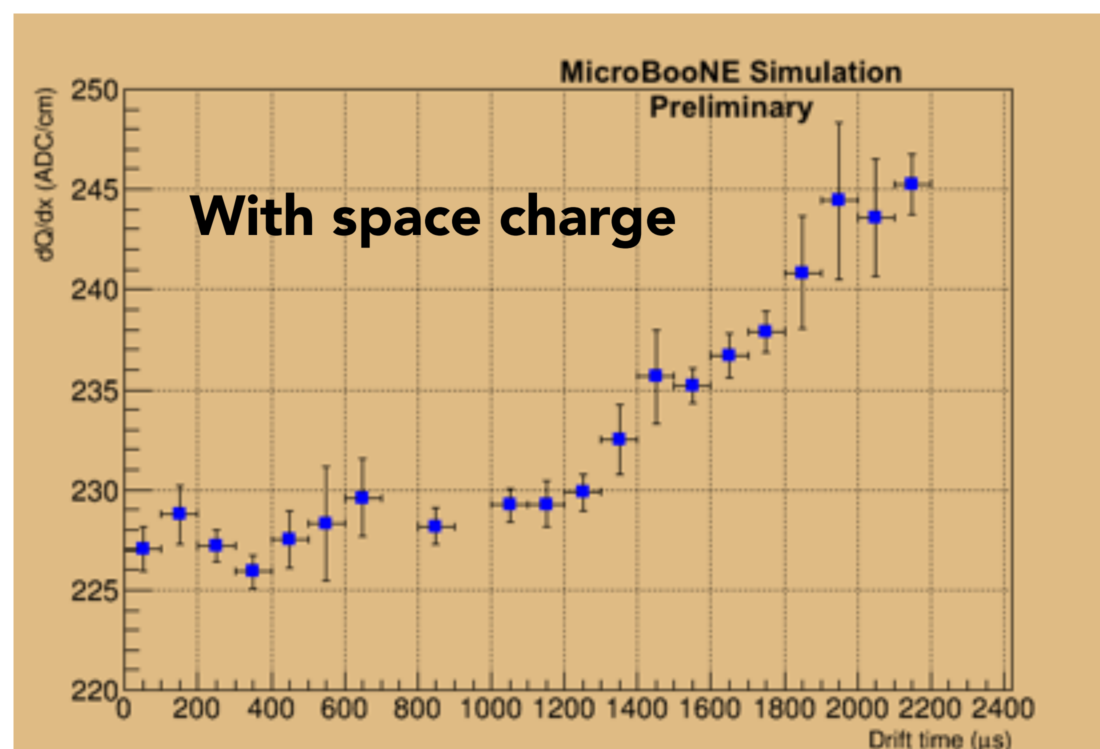


MICROBOONE PUBLIC NOTE 1026

- >18 ms electron lifetime!
- Maximum charge loss 12%
- *MicroBooNE Purification system is performing exceptionally well!*
- Space charge biggest systematic — will improve with future data measurements

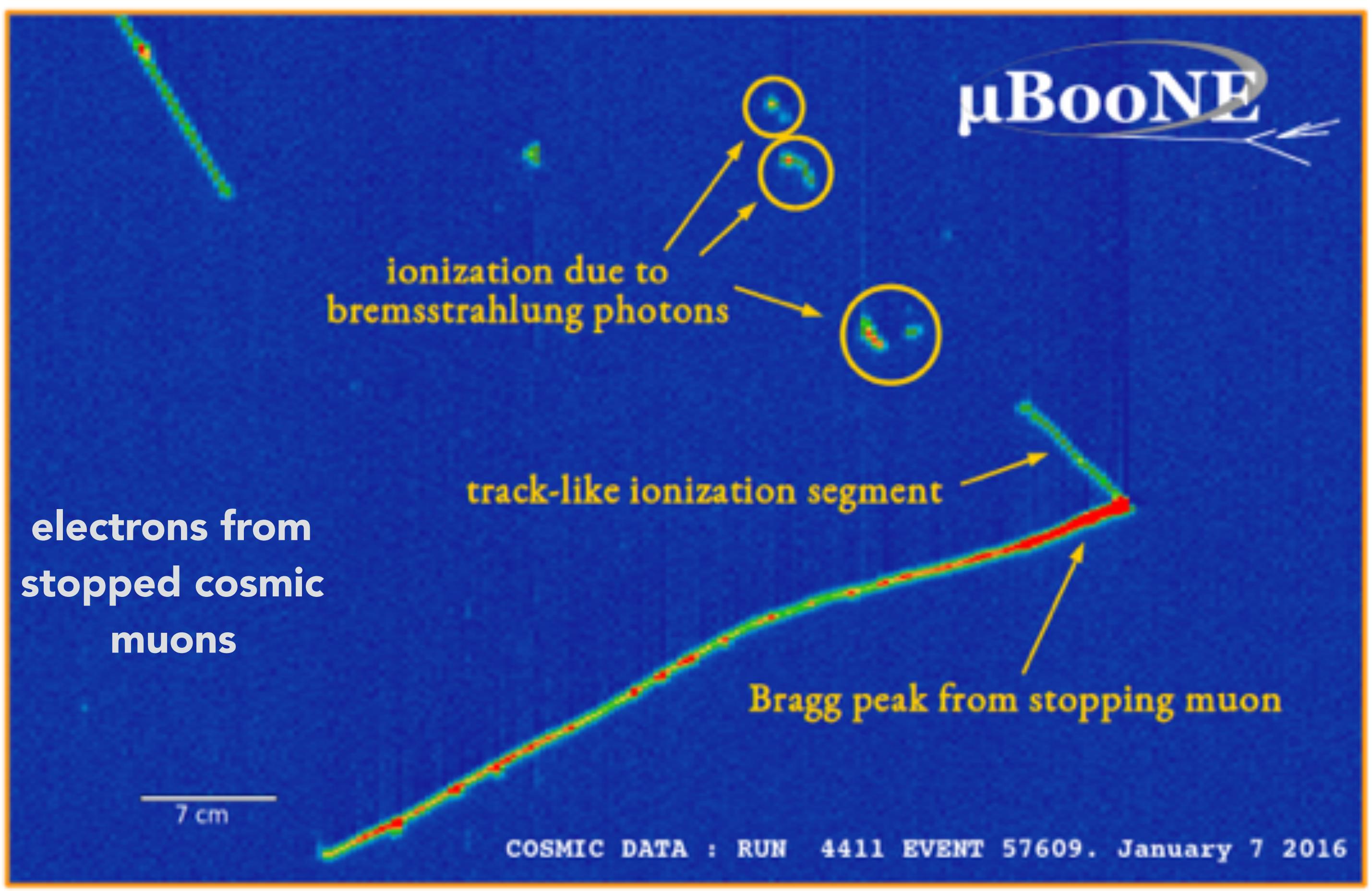


Space charge has significant impact on dQ/dx through recombination

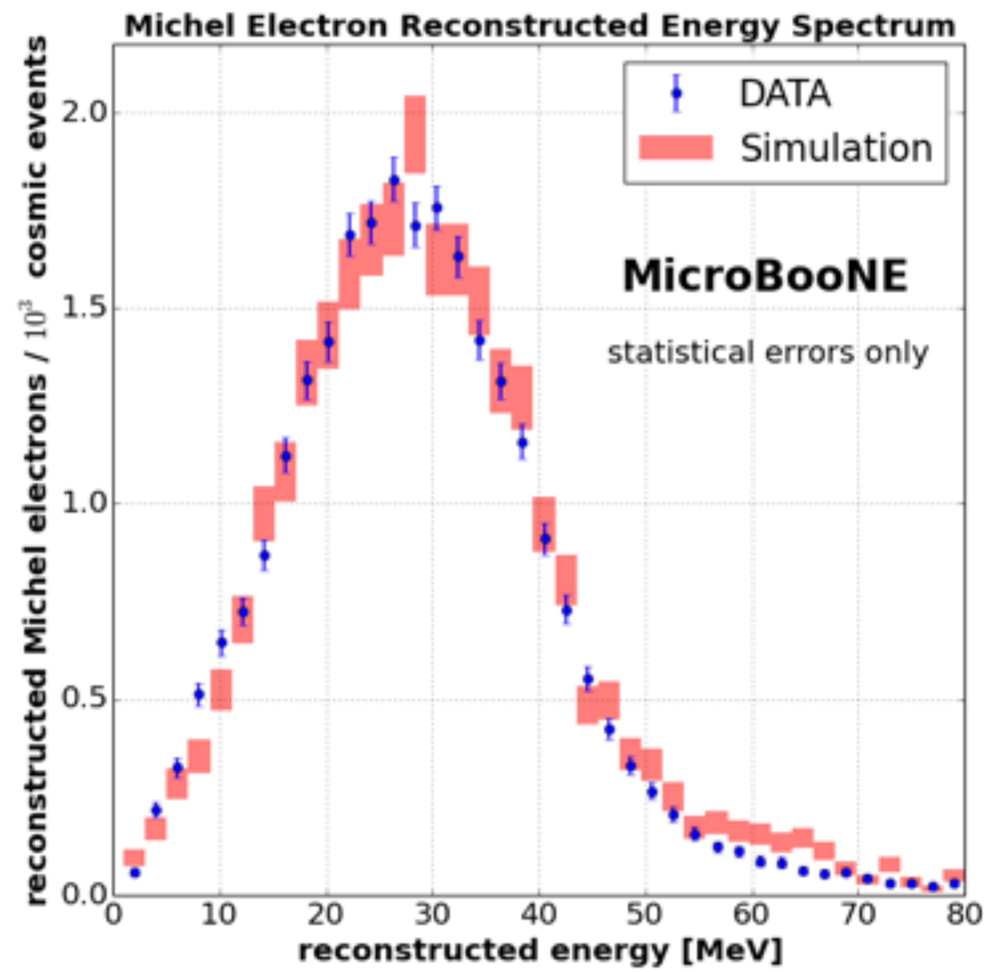


Michel Electrons from Cosmic Data

- Physics Motivation
  - SuperNovae/Low-Energy Physics
  - Study detector response to low energy electrons (up to ~50 MeV)



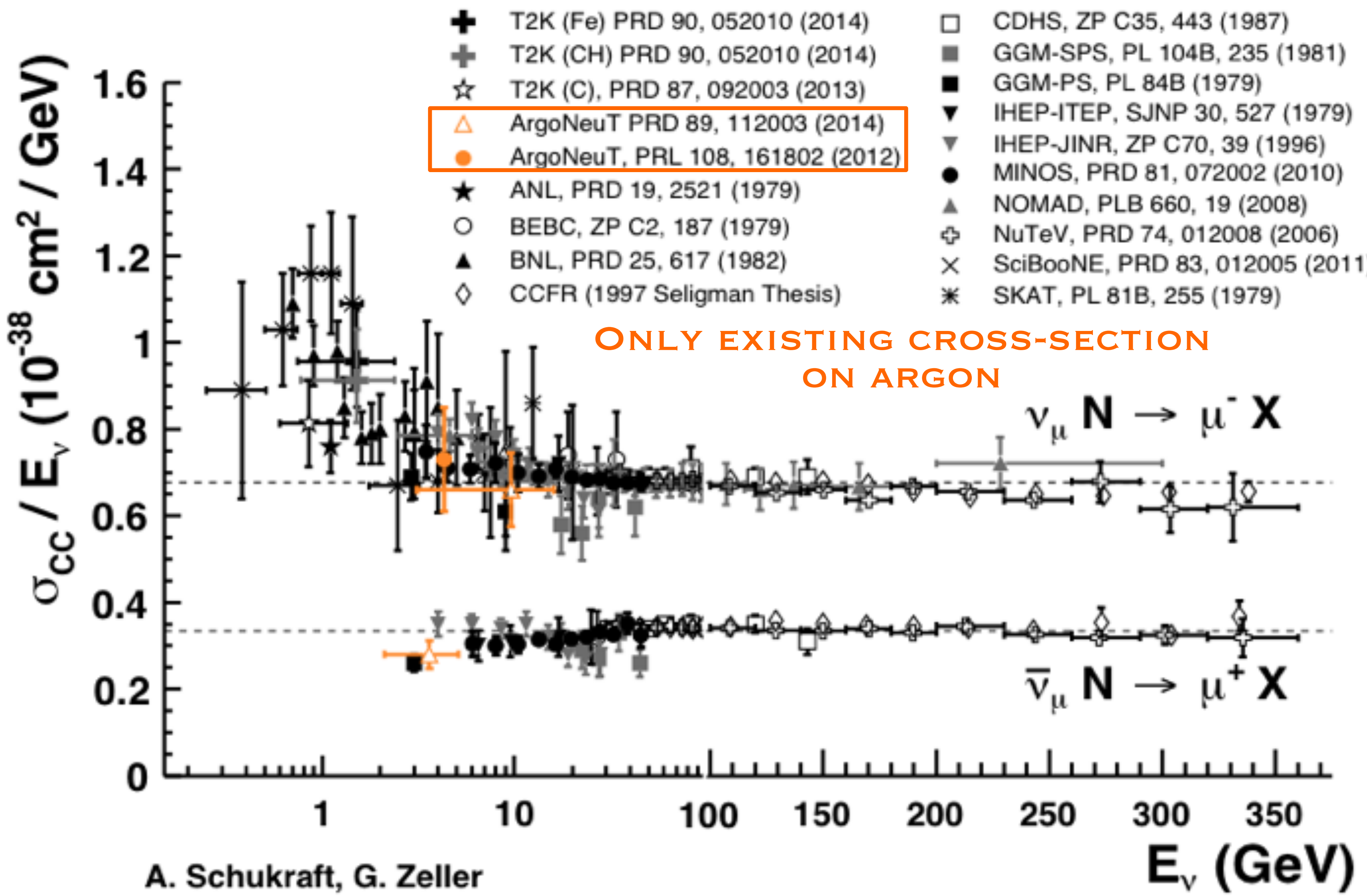
JINST 12 P09014 (2017)



- Complex Reconstruction
- Reconstruction spectrum deficient due to escaping charge from radiative photons
- 20% energy resolution

First study of radiative photons from tens-of-MeV electrons in LArTPC

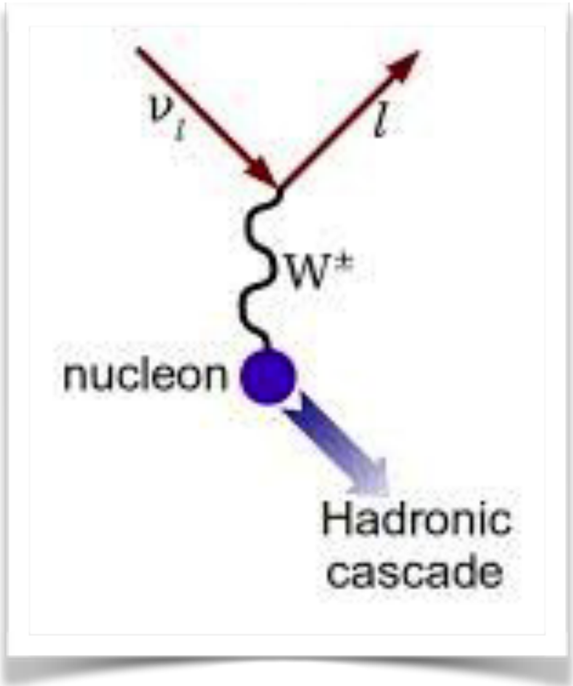
Neutrino Cross-Section data on Argon?



Cross sections are critical for oscillations since counting neutrinos is essentially counting neutrino interaction types

The multi-kiloton LArTPC program critically depends on how much ν-Ar cross-section knowledge we gain in the next few years

First neutrino analysis: Charged Curren ν_μ inclusive



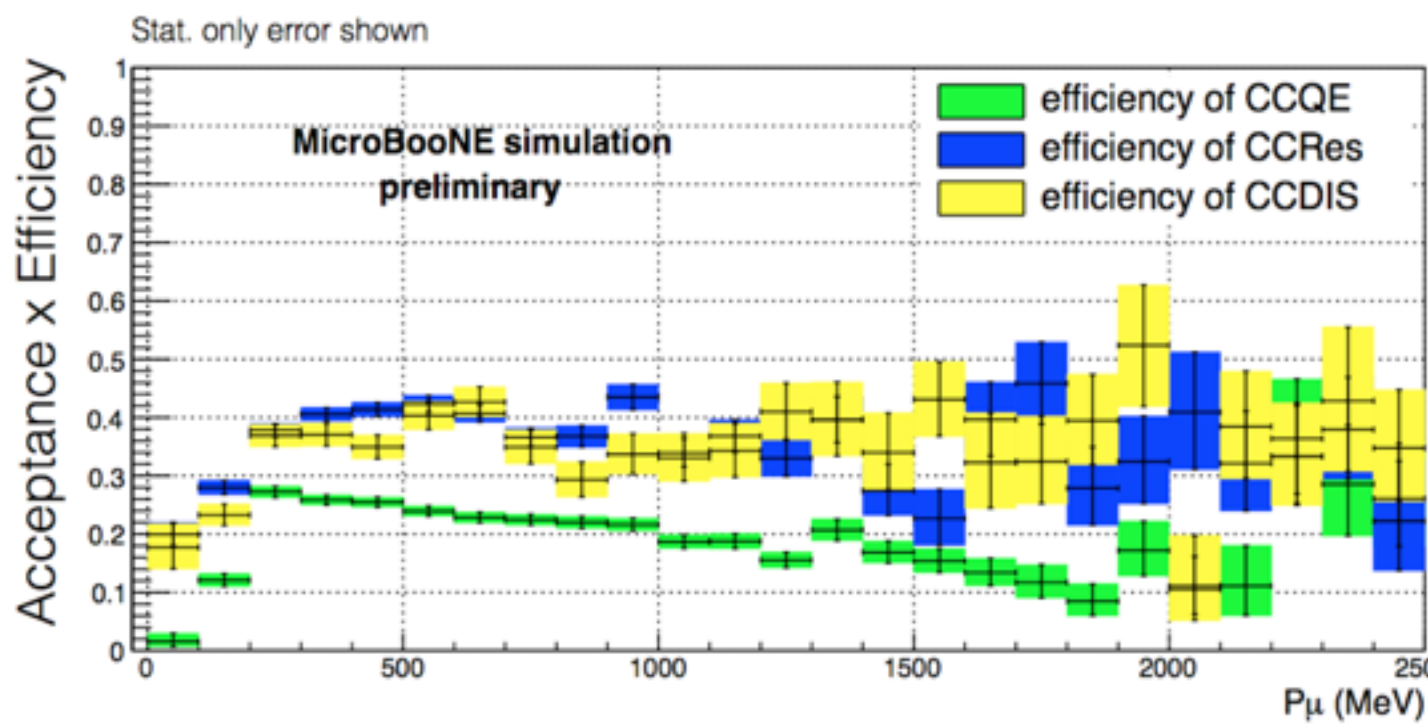
Signature: Look for a muon (plus anything) in the final state with an associated neutrino vertex

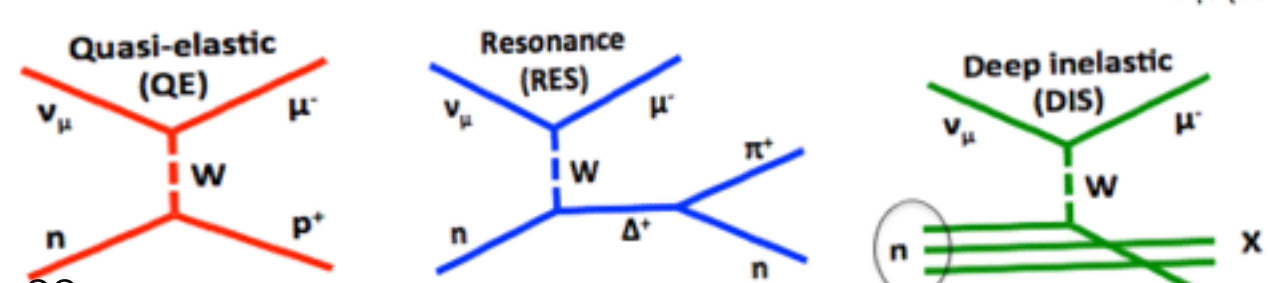
Importance

- First step towards a cross section measurement
- Will develop the reconstruction and systematics tools needed for final state topologies
- Lets you compare data between various experiments

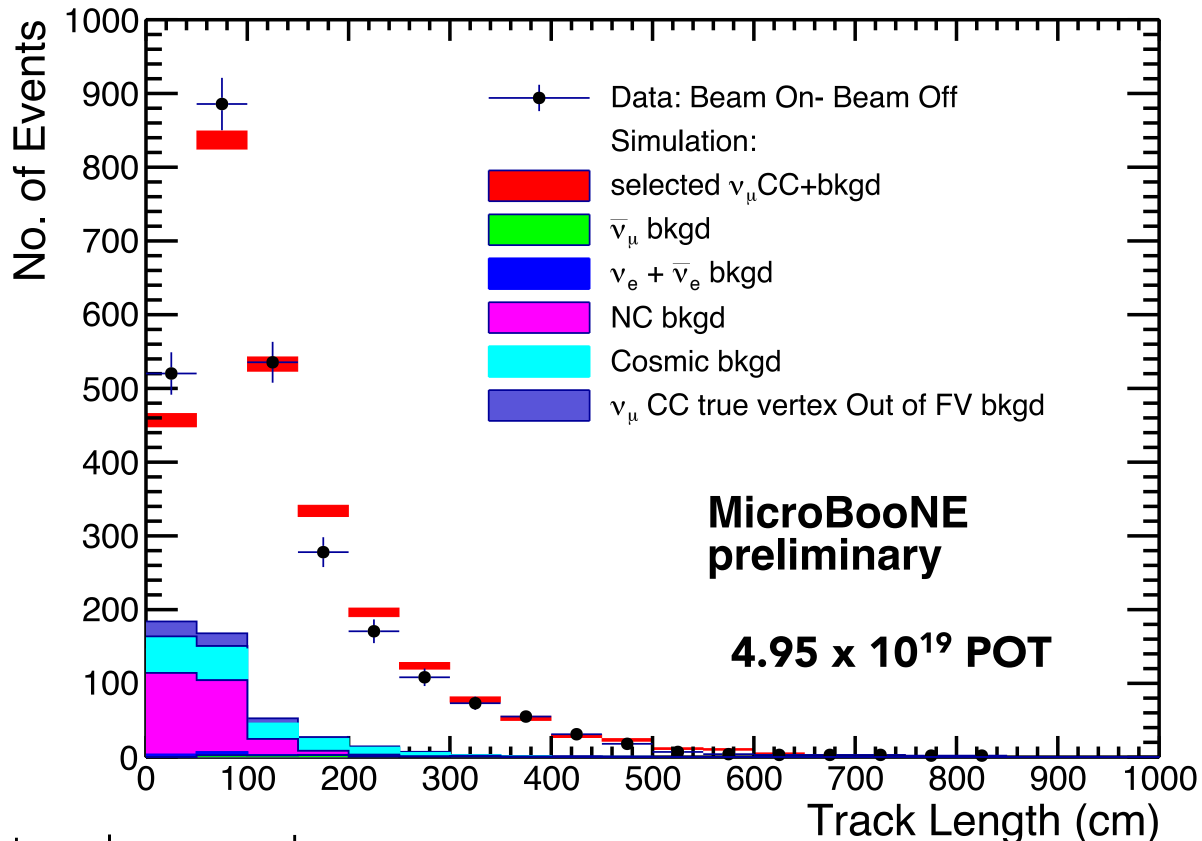
- Fully automated reconstruction & event selection
- *Purity: 60%*
- *Acceptance x Efficiency: 30%*
  - Containment & Min. length cut for 1 track events
  - Cosmic backgrounds a challenge

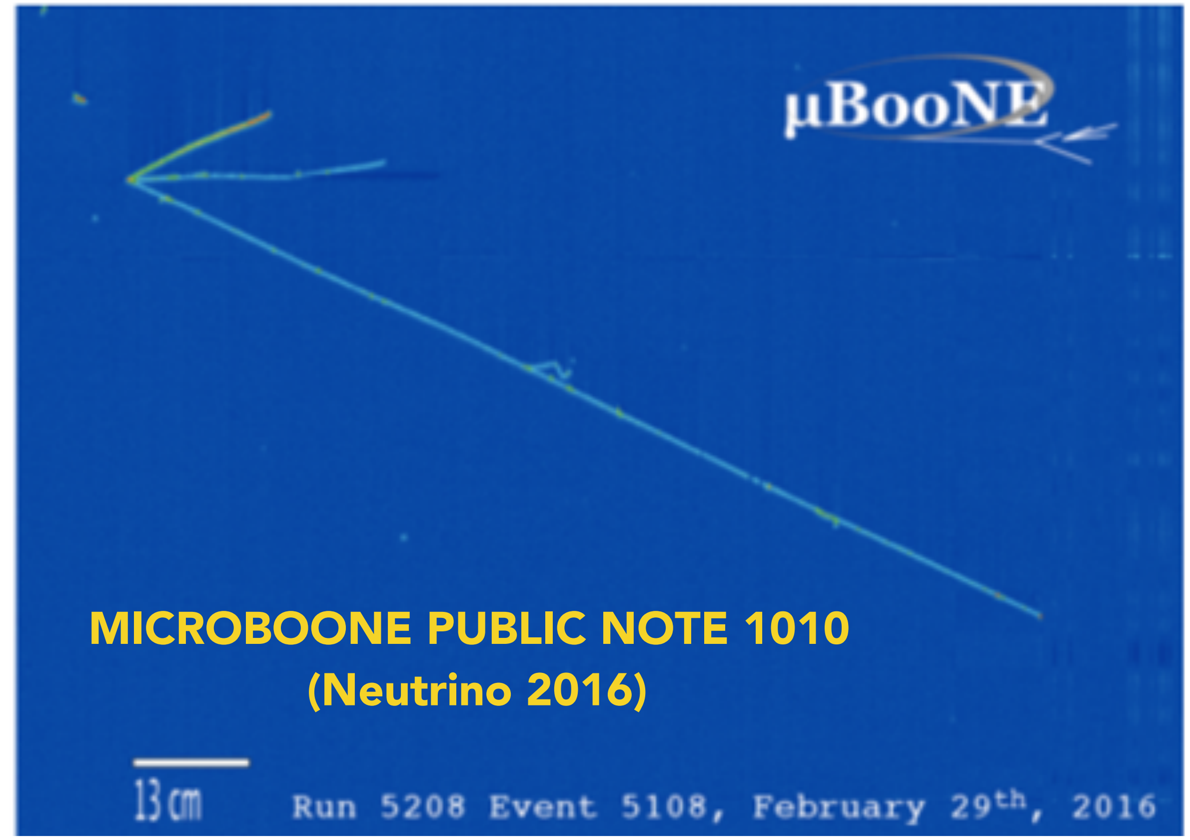
	Before Selection	After Selection
CCQE	60%	43%
RES	30%	42%
DIS	10%	14%



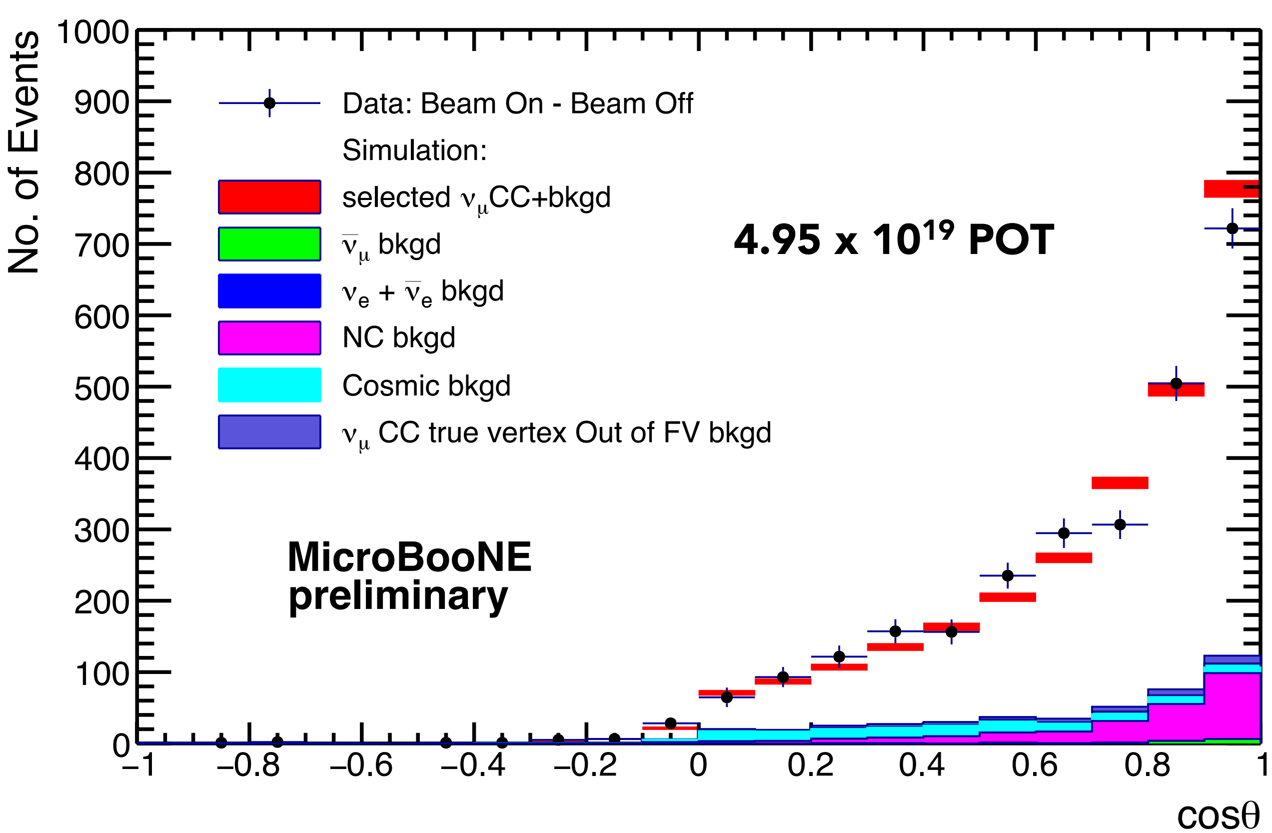


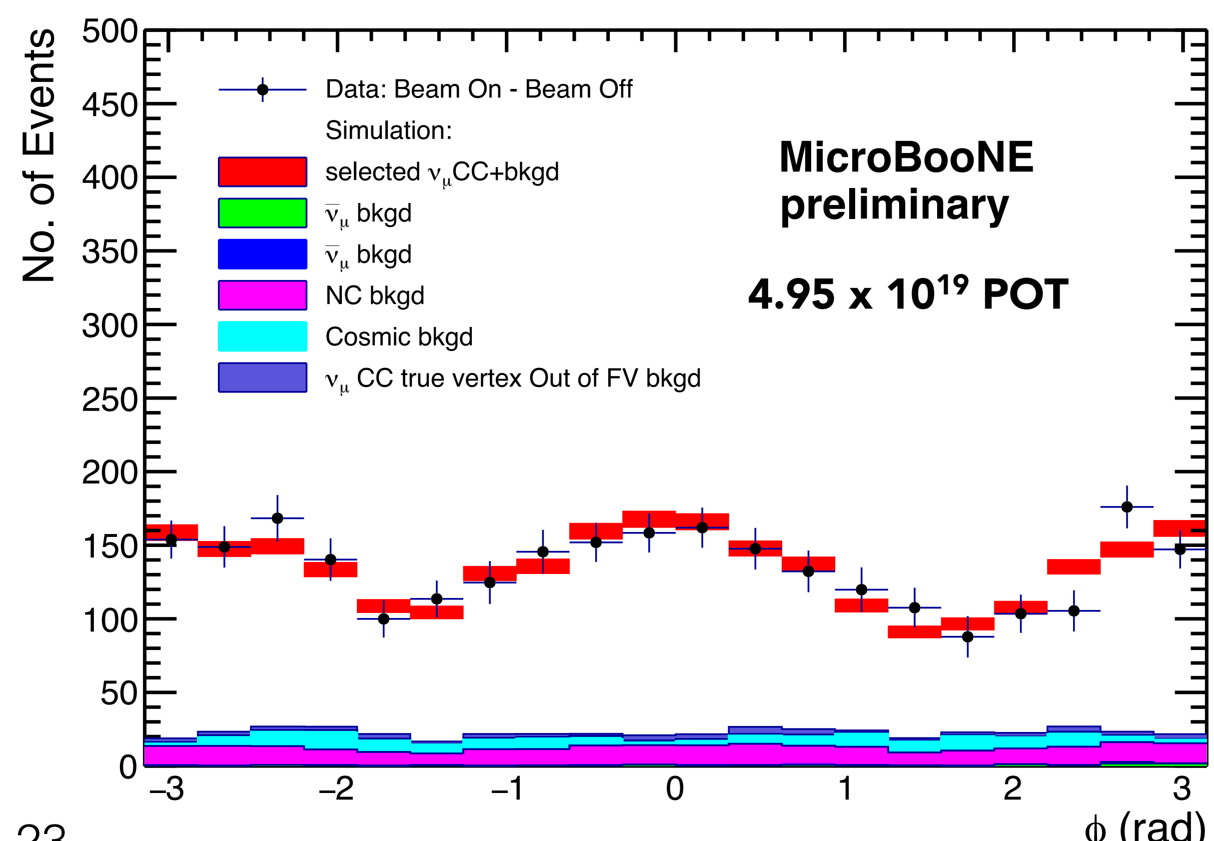
CC ν_μ inclusive event distributions





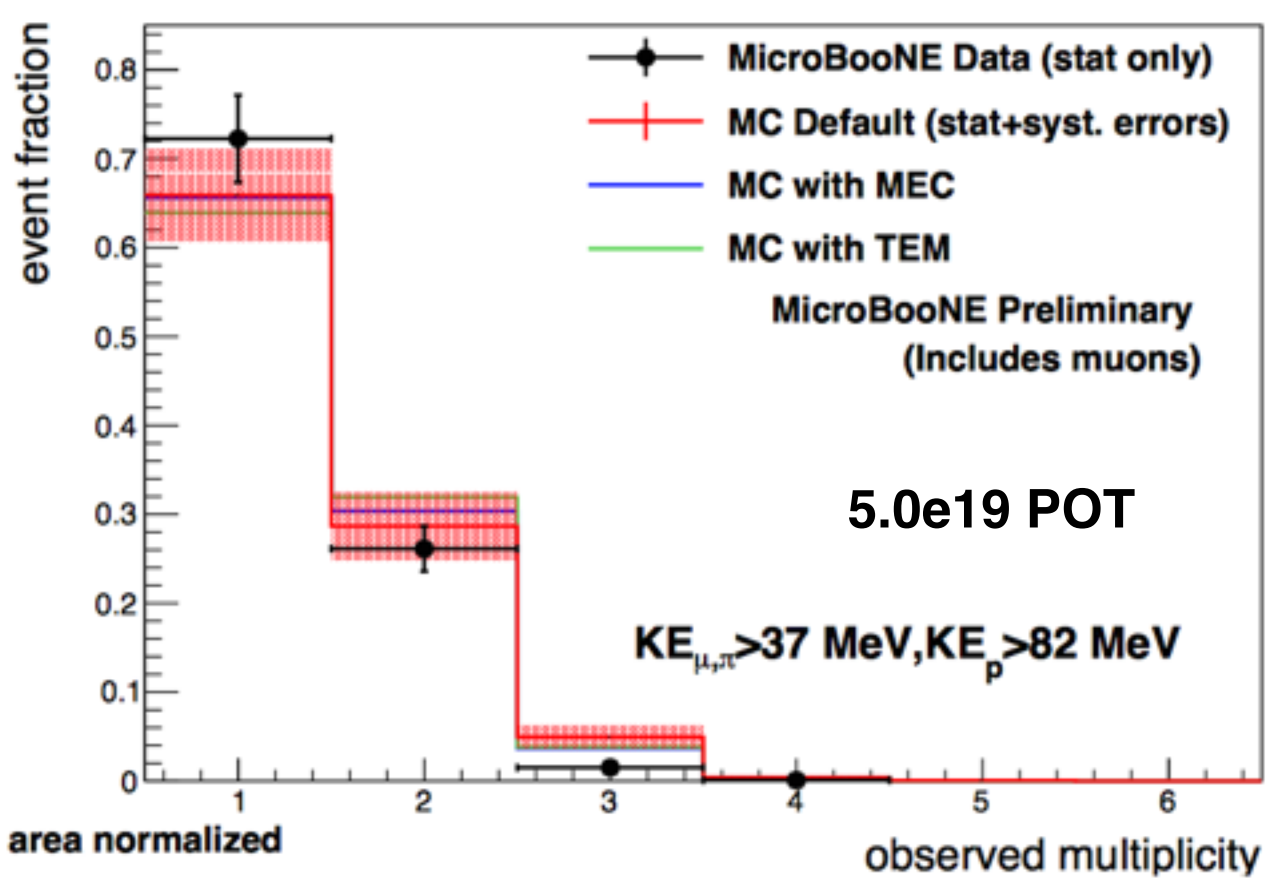
Stat. only error shown

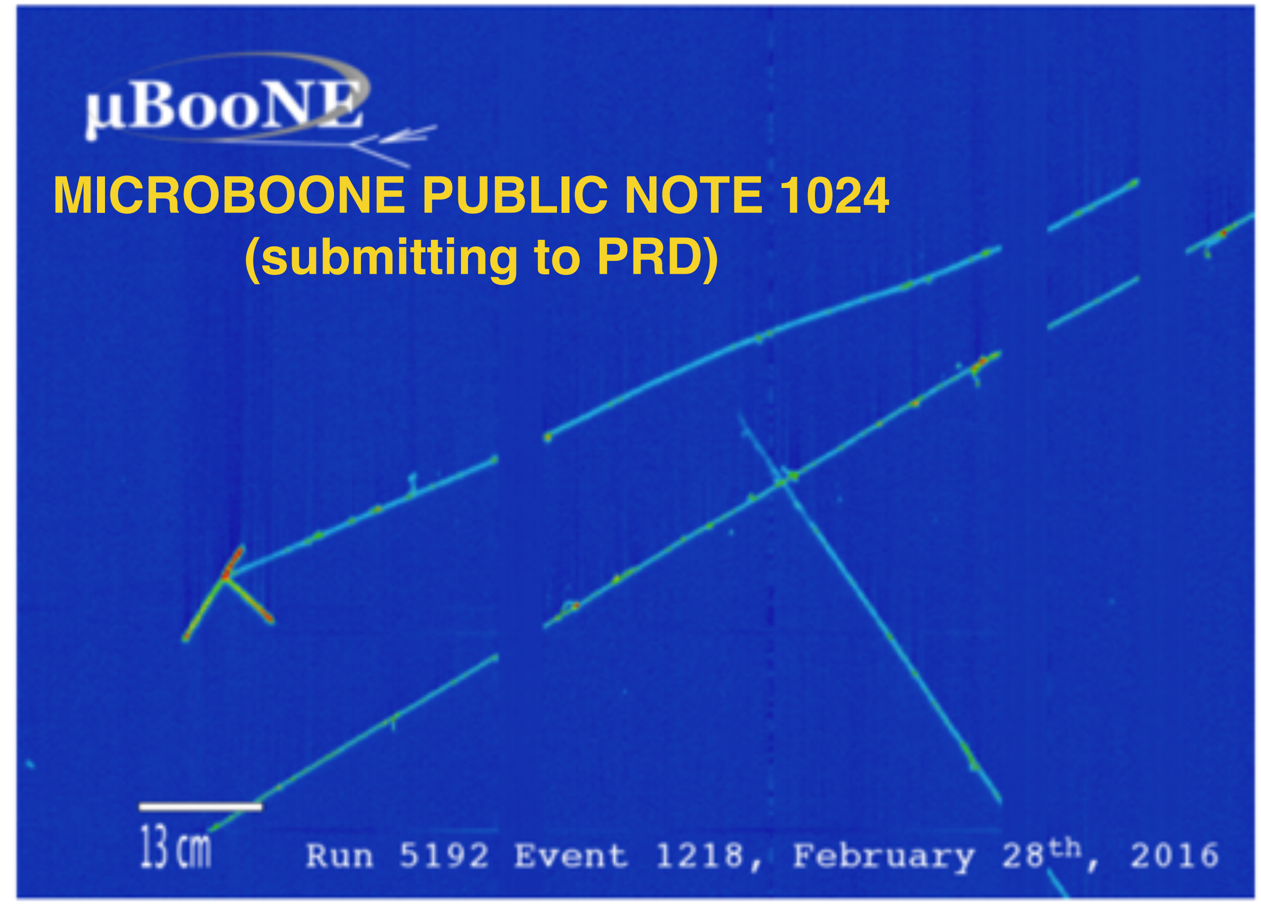




Building on CC ν_μ inclusive analysis: Charged Particle Multiplicity

- Directly observable quantity
- Stringent test for ν event generators inclusively
- Compared charged particle multiplicity from data and different GENIE generator models





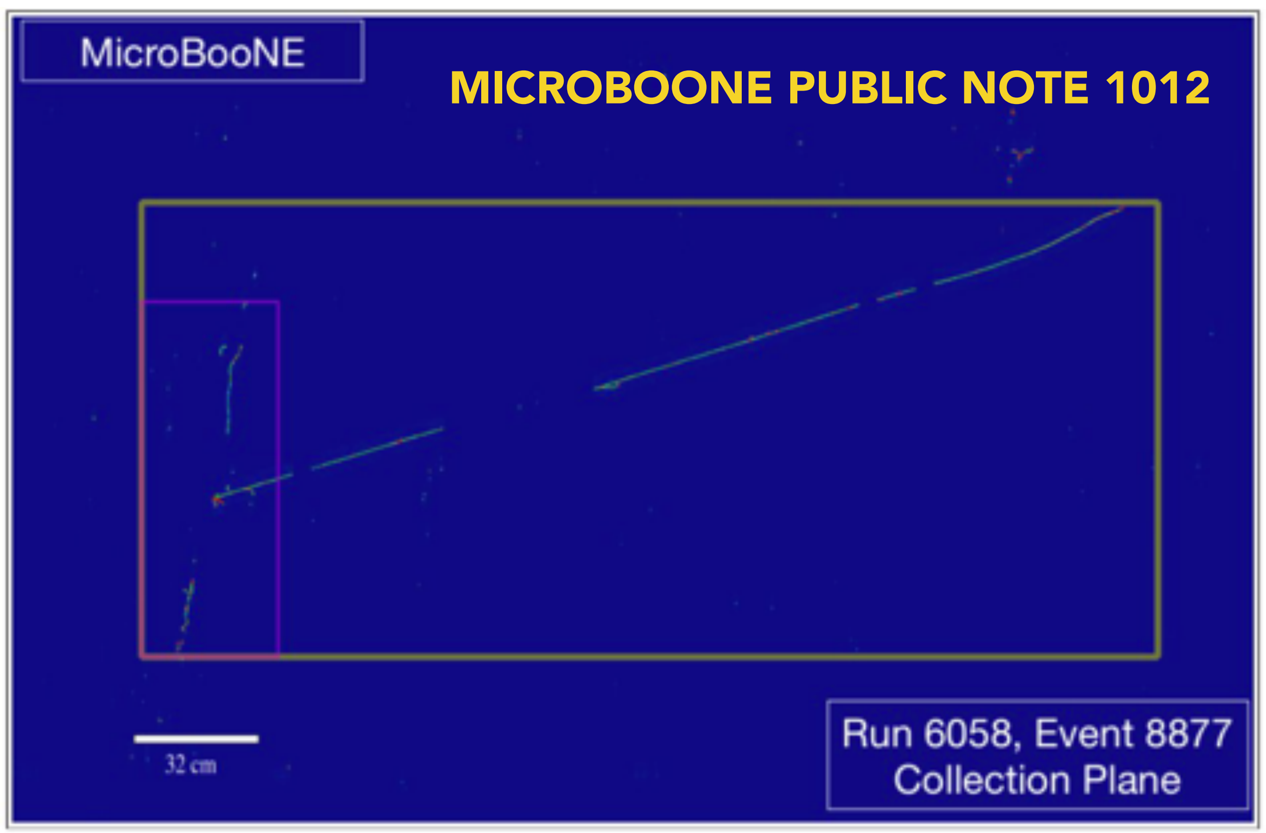
- Some under-prediction and over-prediction
- Future comparisons will involve more widely varying model predictions

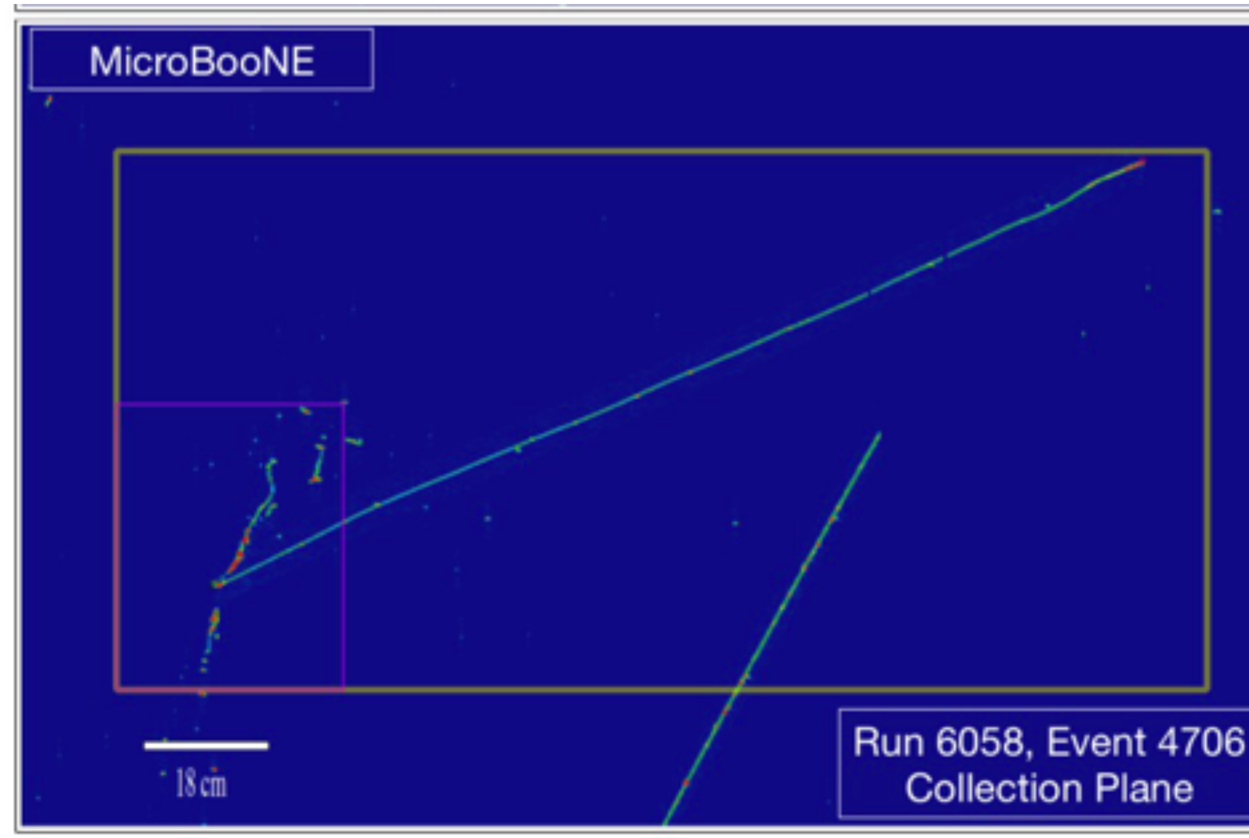
First measurement of charged track multiplicity in ν_μ CC interactions in Ar

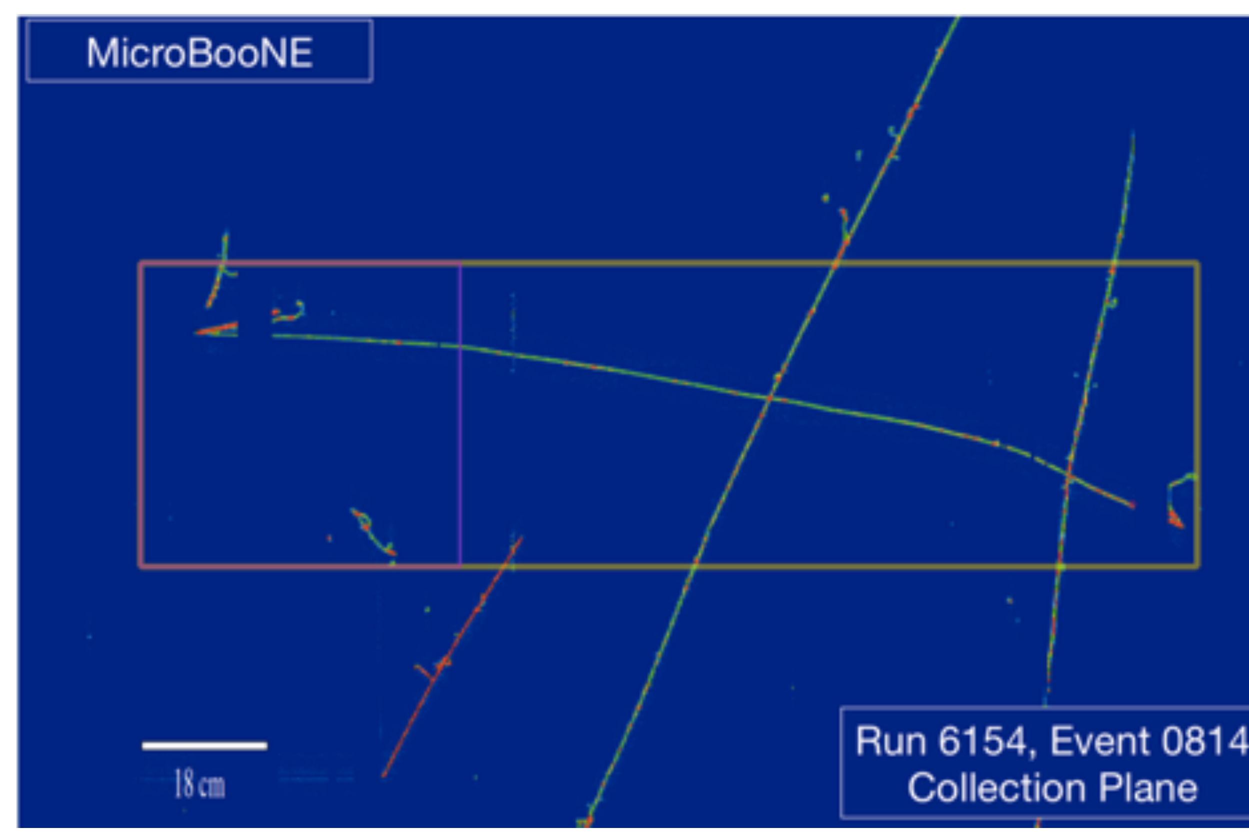
Building on CC ν_μ inclusive analysis: Charged Current π^0 events

Key sample towards developing low energy excess analysis

- Study shower reconstruction performance
- Energy calibration tests with π^0 mass peak
- NC π^0 background estimation



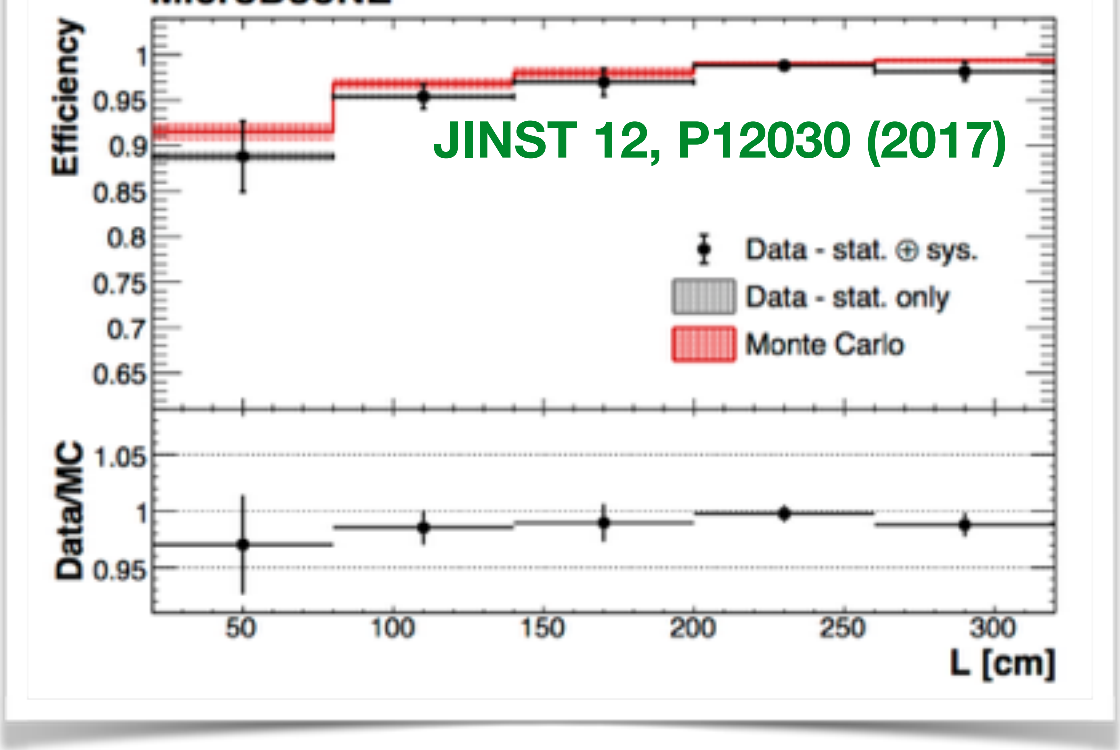




Currently working towards world's first measurement of CC π^0 cross-section measurement on argon

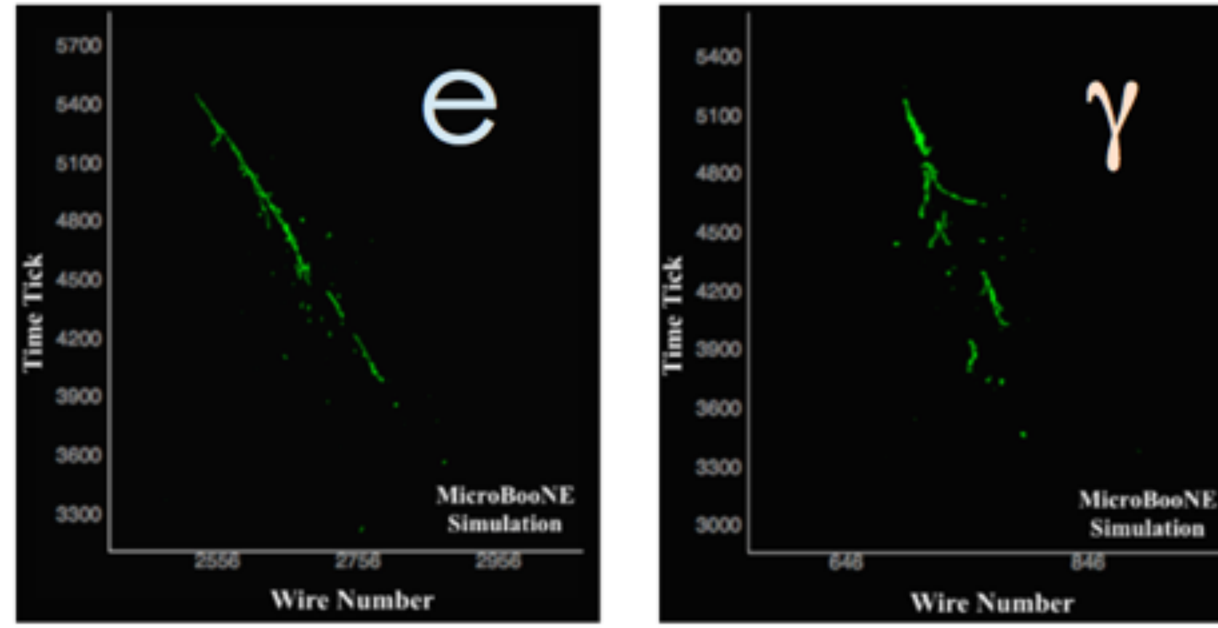
Reconstruction & Particle ID

Muon tracking efficiency

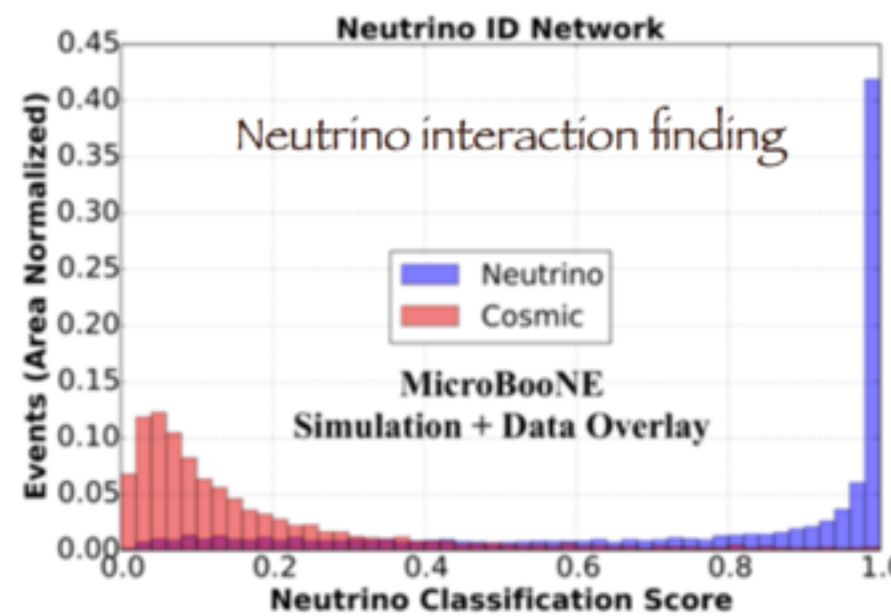


JINST 12, P12030 (2017)

Deep Learning techniques



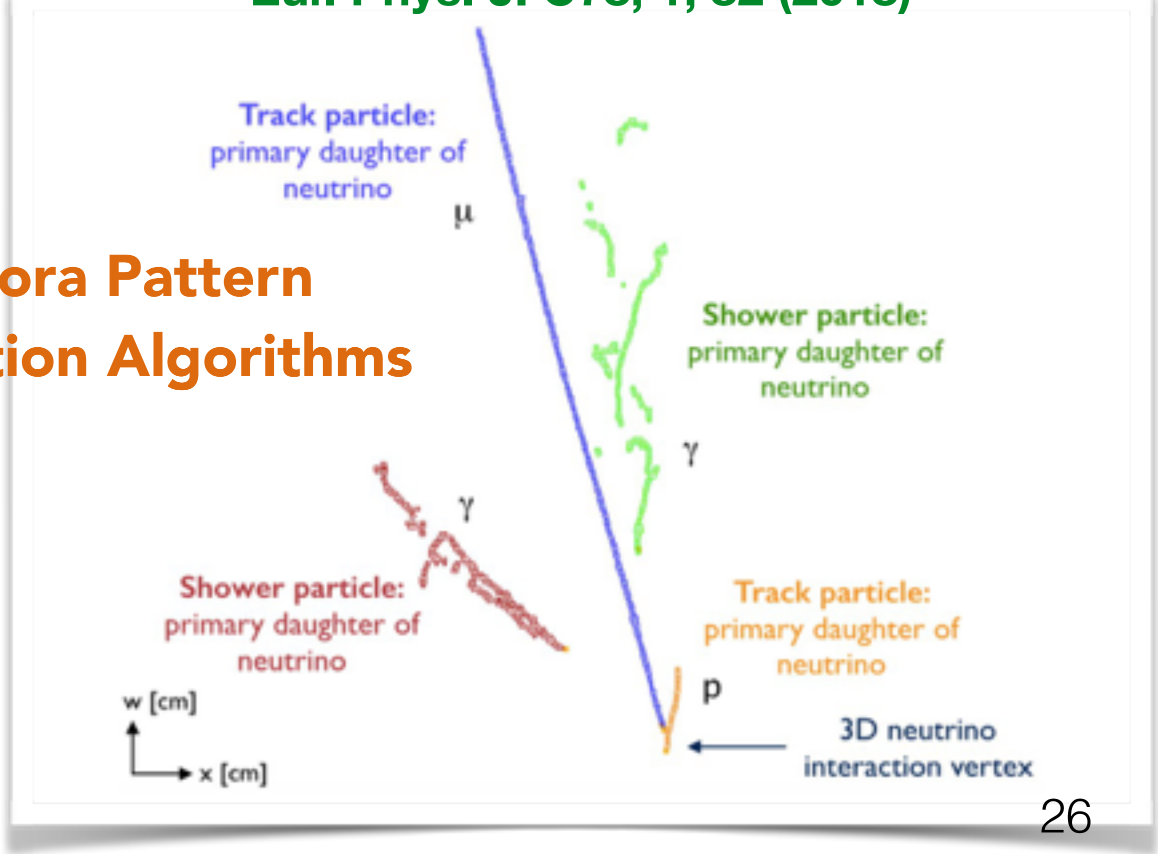
JINST 12, P03011(2017)



Developing multiple approaches for the flagship oscillation analysis

Pandora Pattern Recognition Algorithms

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



Summary

- MicroBooNE is taking data stably since August 2015 and is continuously analyzing it at all levels
- Made enormous progress in understanding the detector and the technology
- Automatic Reconstruction algorithms Performing well and are continuously being improved
- Cosmic backgrounds being mitigated by the external large Cosmic Ray Tagger System
- Many more analyses in pipeline, Stay tuned for more exciting results from MicroBooNE soon!
- MicroBooNE is in an excellent place to address both ***technical*** and ***measurement*** challenges for both SBN and the multi-kiloton long-baseline DUNE program

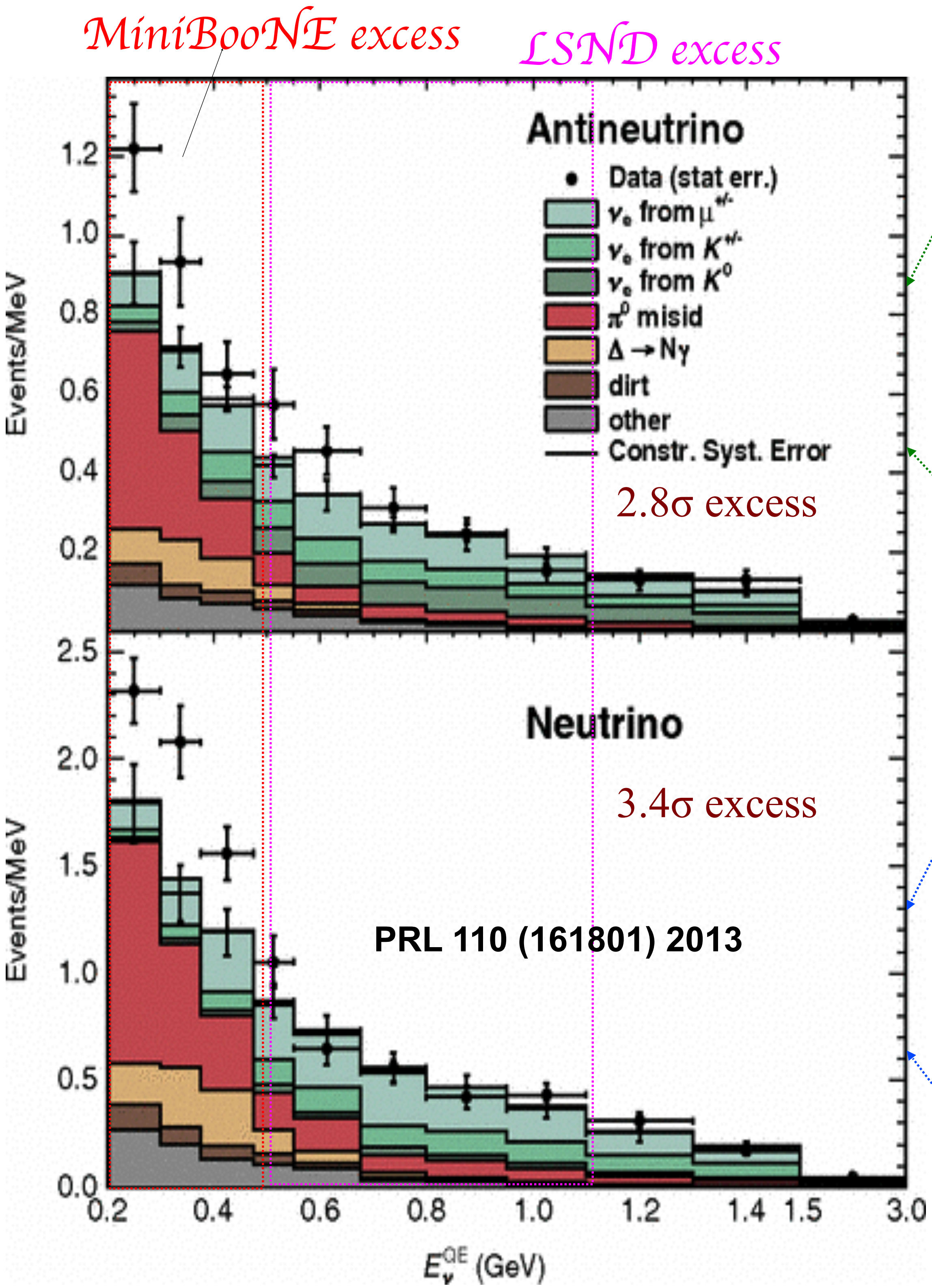
Thank you!

Backup

High Δm^2 results: the MiniBooNE experiment

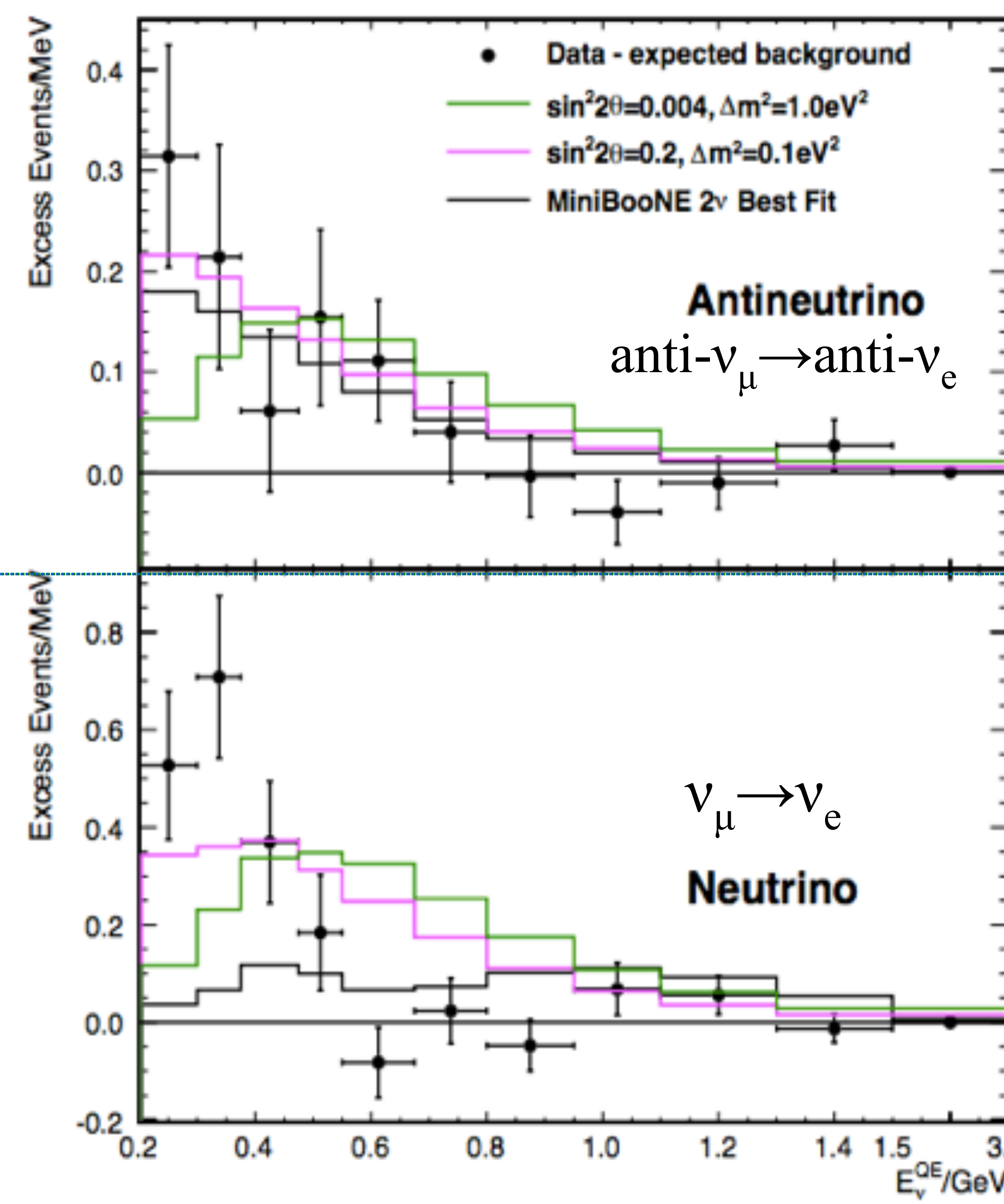
Same L/E_ν (~ 1m/MeV) as LSND – entirely different systematics and backgrounds than LSND

Water Cherenkov Detector



Subtract background from data

data are consistent with anti-**ν** oscillations in the $0.01<\mathbf{\Delta m^2}<1.0$ eV^2 range. Some overlap with LSND

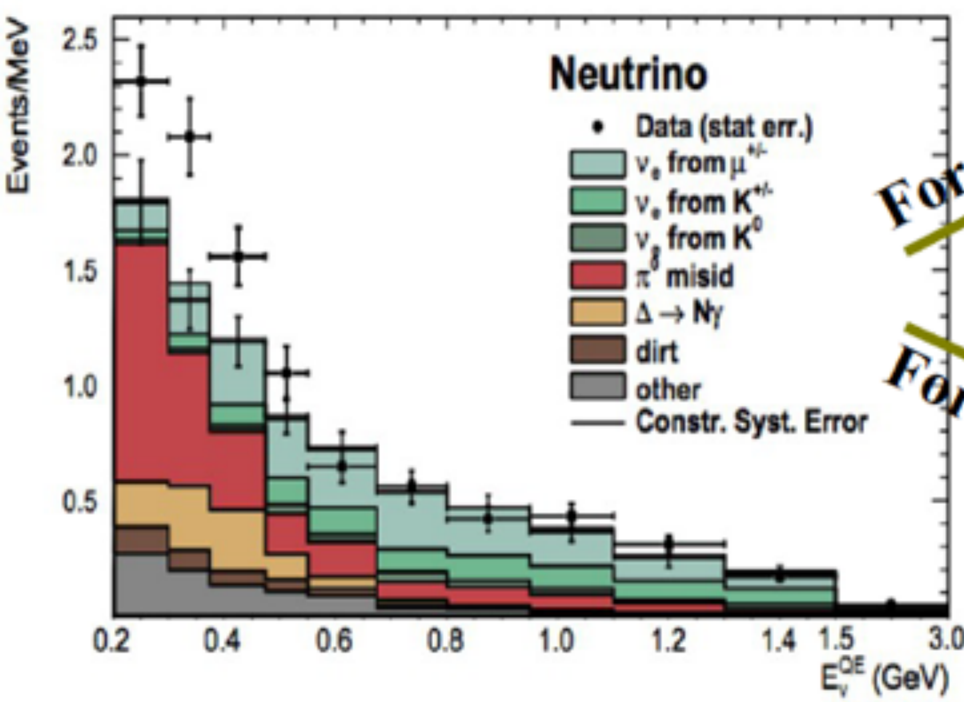


Excess is only marginally compatible with simple 2-ν oscillation formalism

a

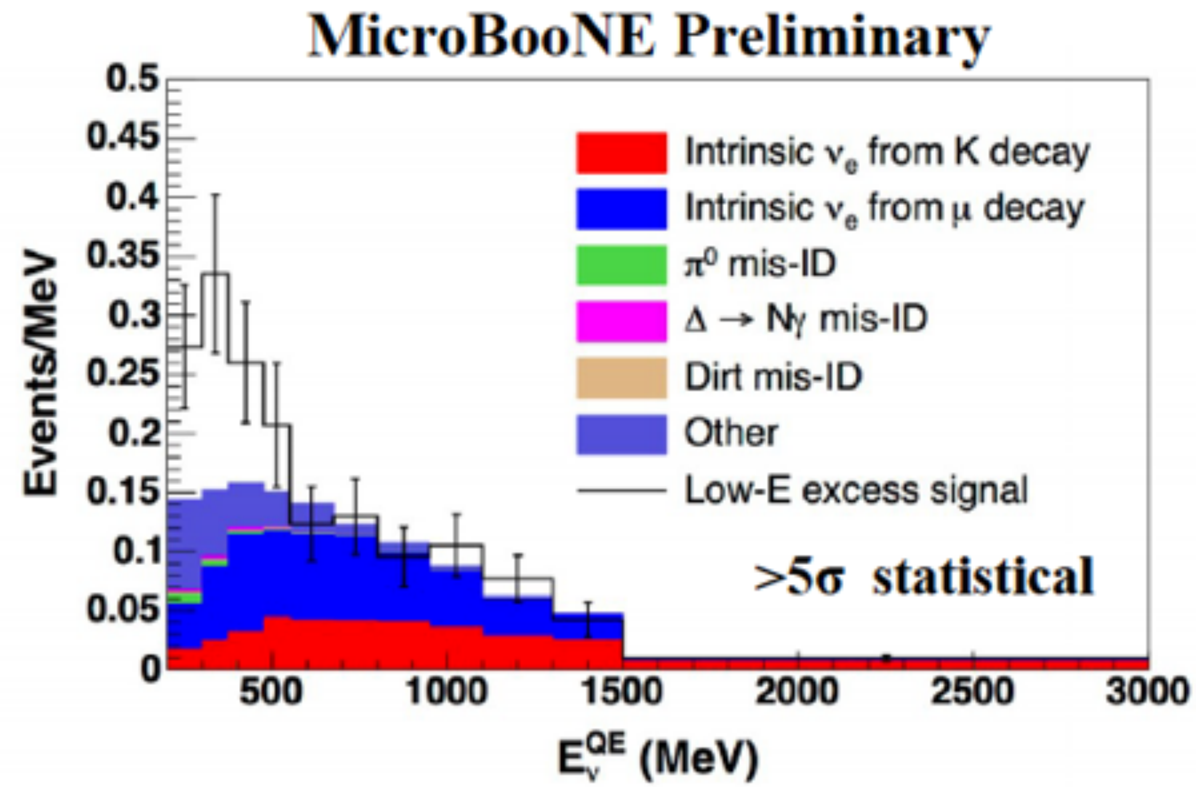
What can MicroBooNE tell us about the MiniBooNE low-E excess?

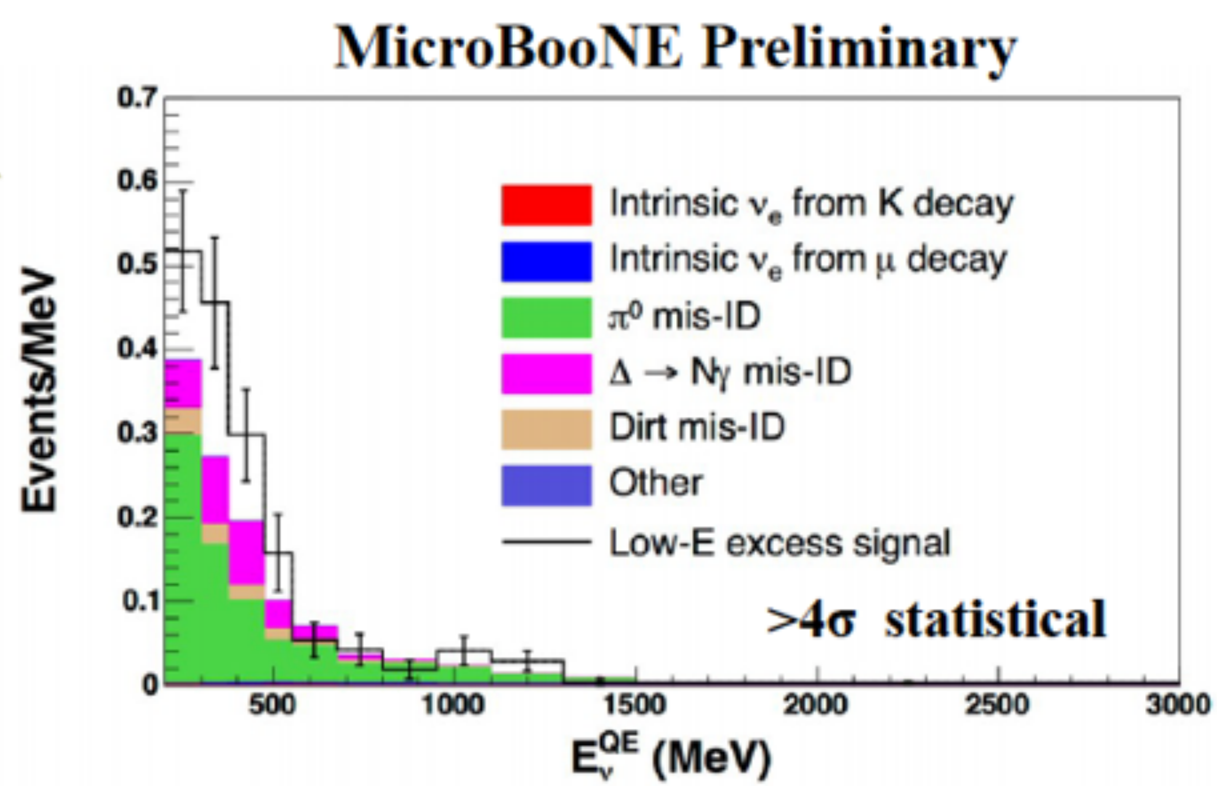
MicroBooNE is capable of telling us whether the excess is electron-like or photon-like



For an e-like excess

For a γ-like excess

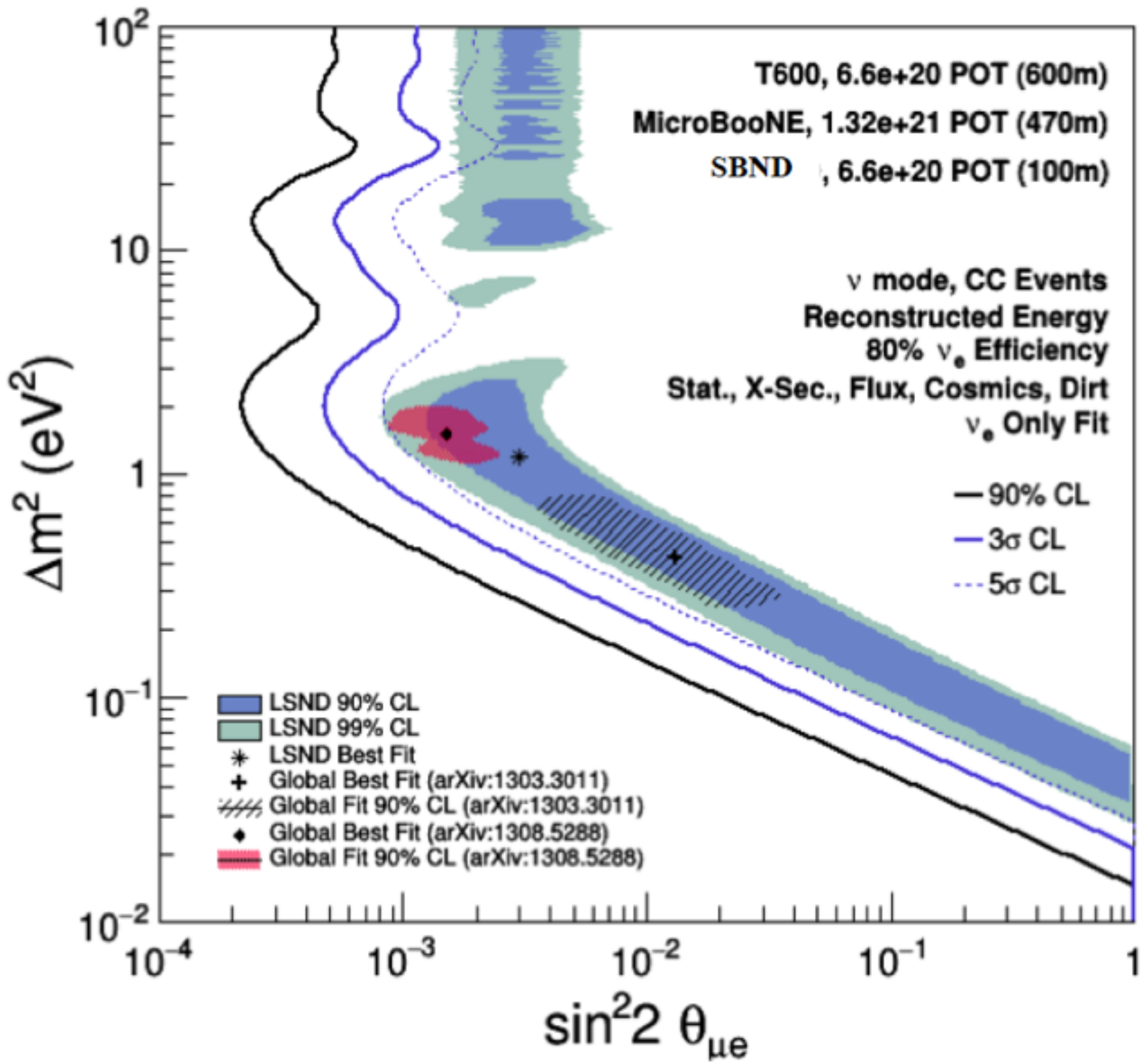




While MicroBooNE can address a critical piece of short-baseline puzzle, **MicroBooNE by itself is not enough to explore the complete sterile neutrino oscillation parameter space**

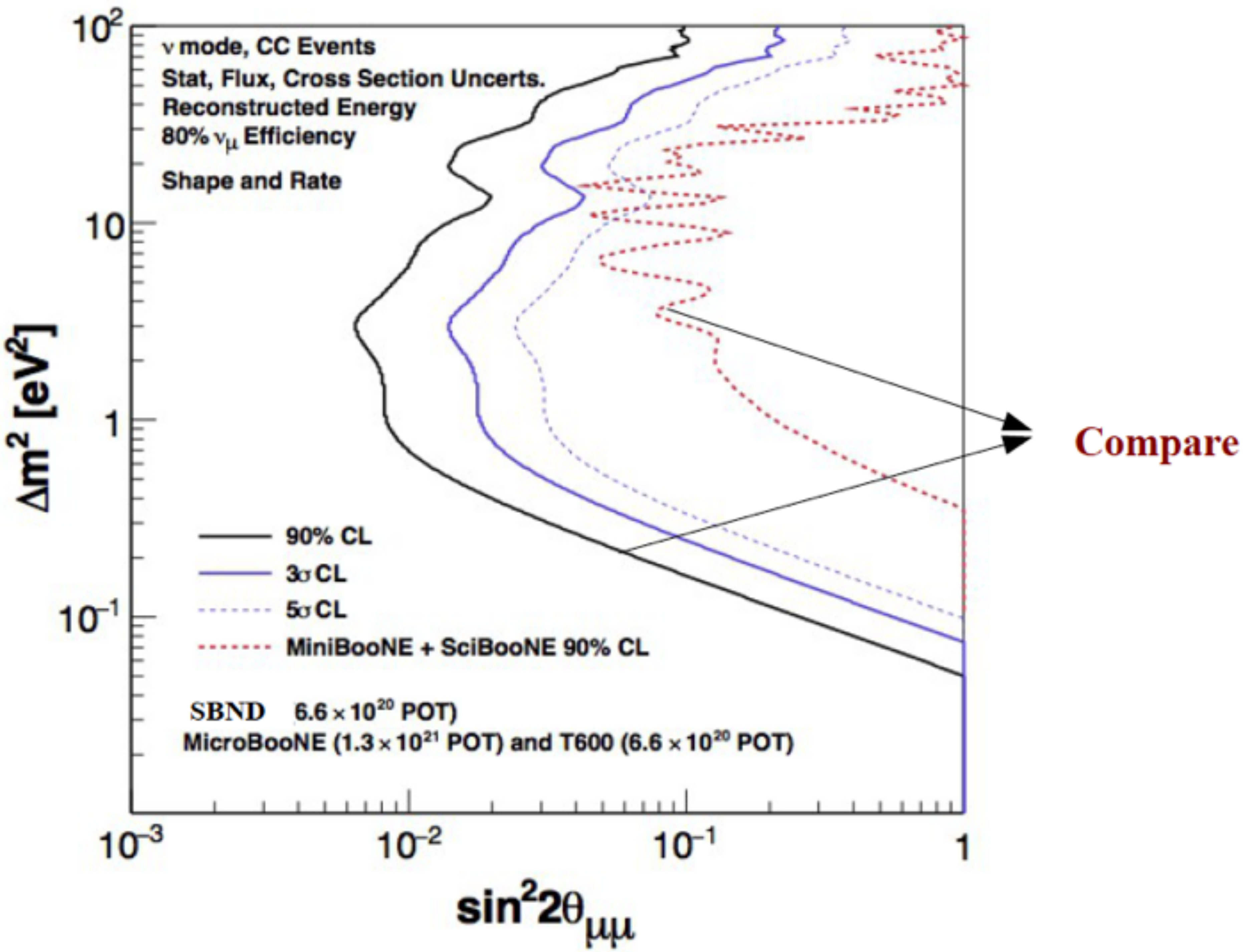
SBN: $\nu_\mu \rightarrow \nu_e$ appearance sensitivity

The LSND 99% C.L. allowed region is covered at the ≥ 5σ level above $\Delta m^2 = 0.1$ eV^2



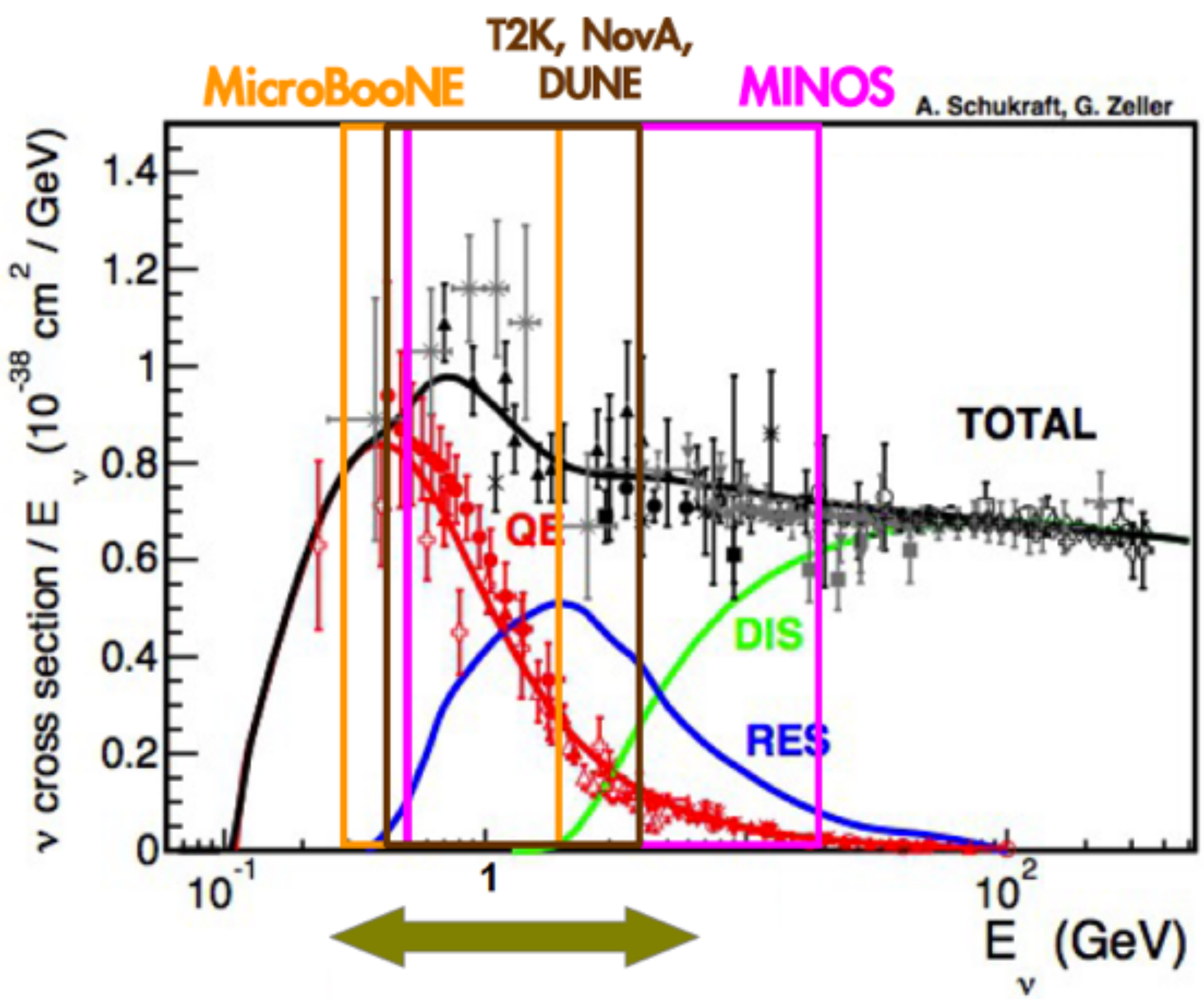
SBN: ν_μ disappearance sensitivity

SBN can extend the search for muon neutrino disappearance an order of magnitude beyond the combined analysis of SciBooNE and MiniBooNE.



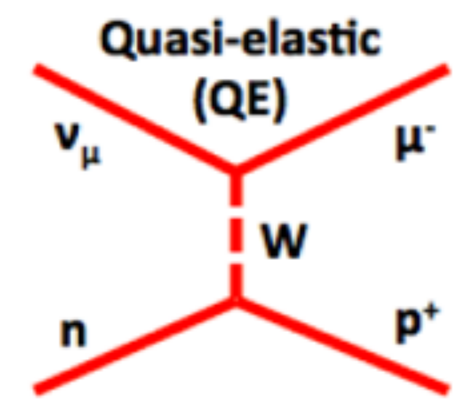
Neutrino-Argon Interactions

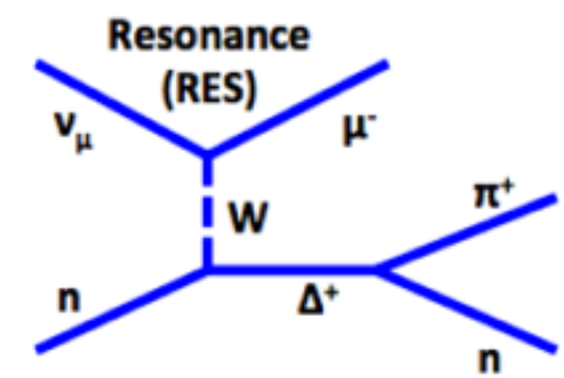
Understanding ν-N cross-sections over the energy range valid for short and long baseline experiments is vital for any oscillation measurement!

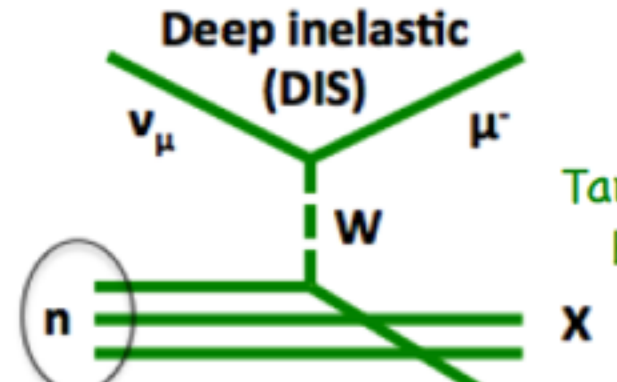


Competitive physics processes and complicated nuclear effects in the 1 GeV range!

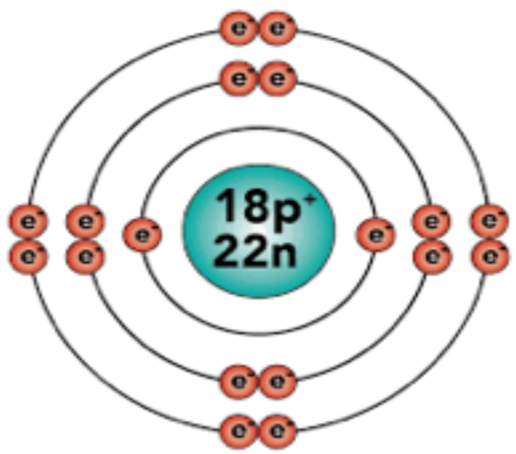
Neutrino-nucleus interactions







Why Liquid Argon as nuclear target?



- *dense & Abundant (1% of atmosphere)*
- *easily ionizable (55,000 electrons/cm)*
- *highly scintillating (transparent to light produced)*
- *Pure argon results in high electron mobility => long drift lengths*

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

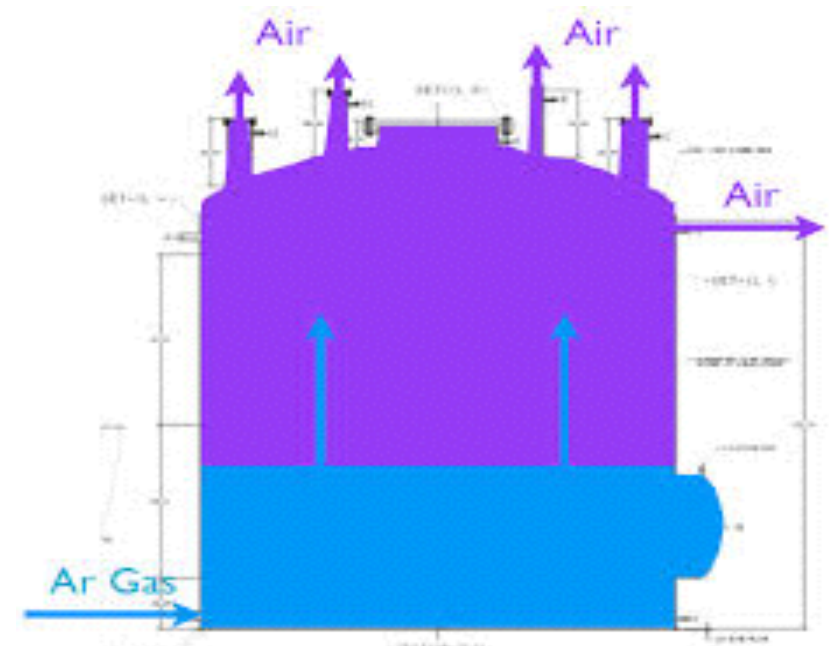
CREDIT: M. SODERBERG

Major R&D milestones from MicroBooNE

Surge protection devices

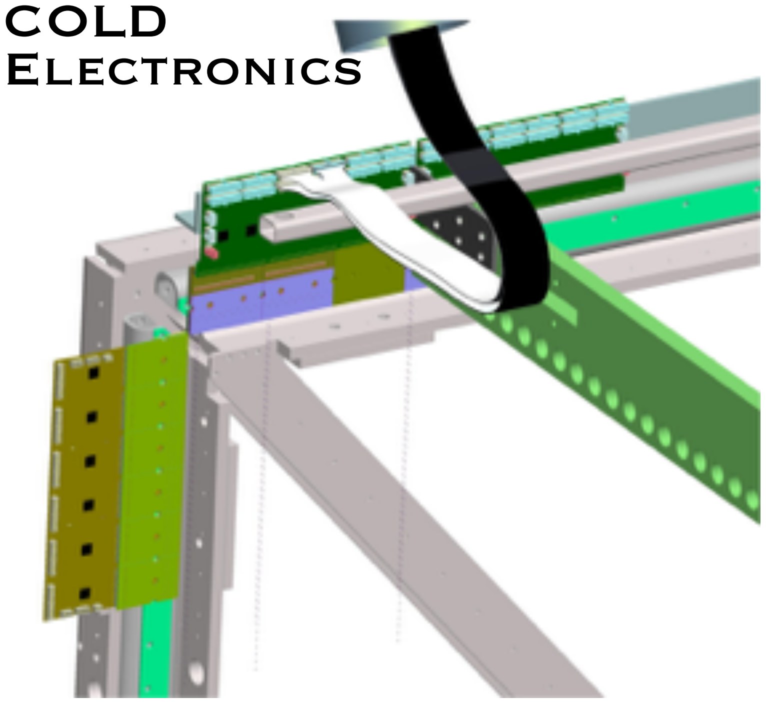
S. Gollapinni *et al.*,
JINST 9, T11004 (2014), JINST 9 P09002 (2014)

Purity without evacuation



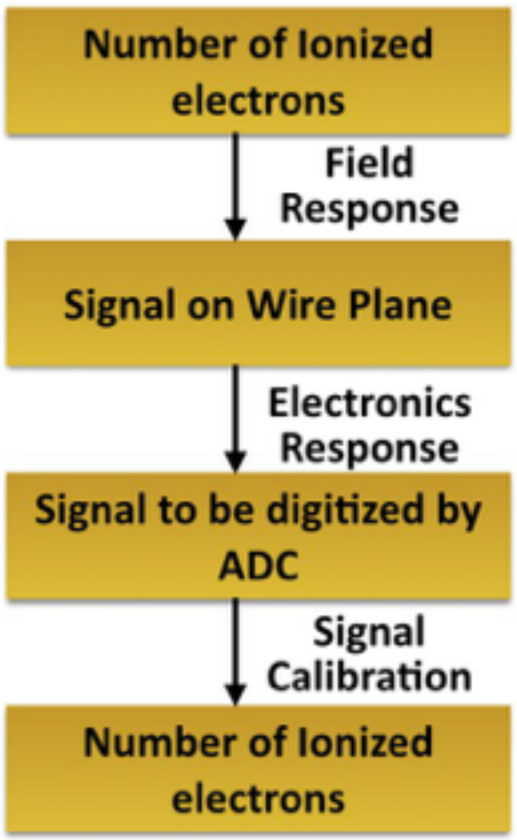
Successful design & Installation of the 1st 100-ton scale TPC in the U.S.

Cold Electronics



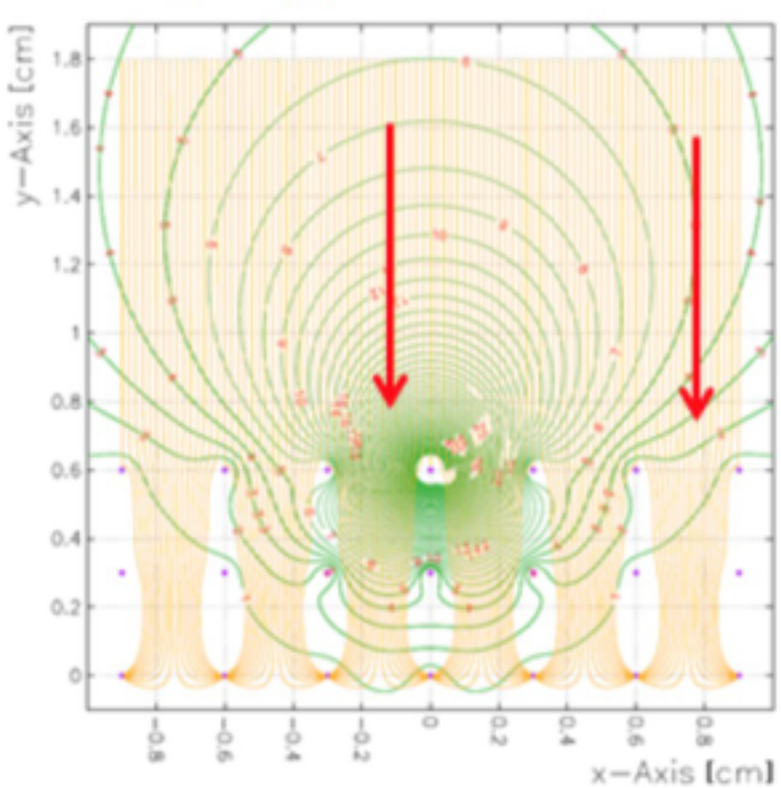
Cryogenics

TPC Signal Processing

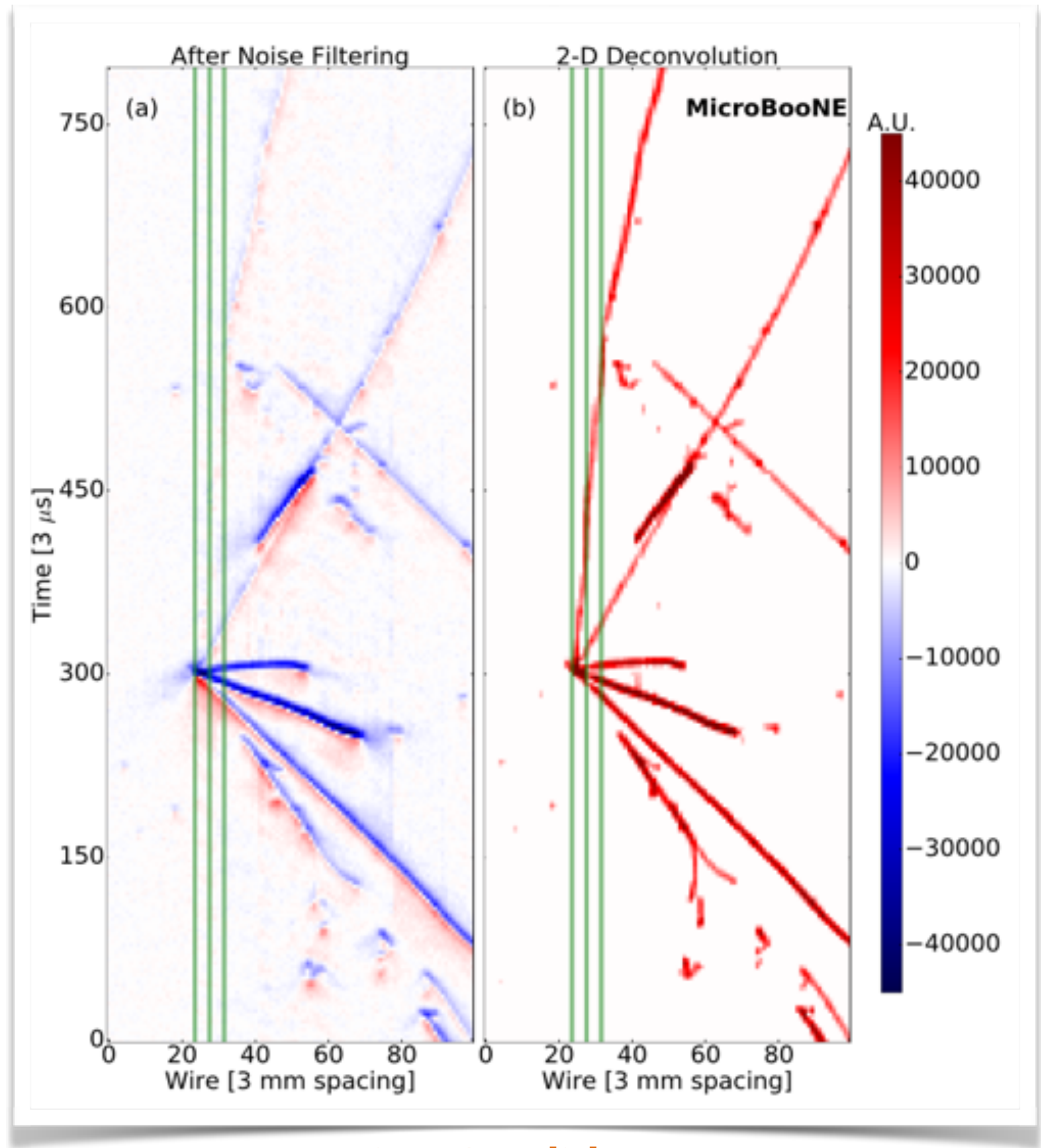


Typically expect signal to be induced on only one wire. But, in reality, nearby wires also see some signal

Weighting potential of a wire



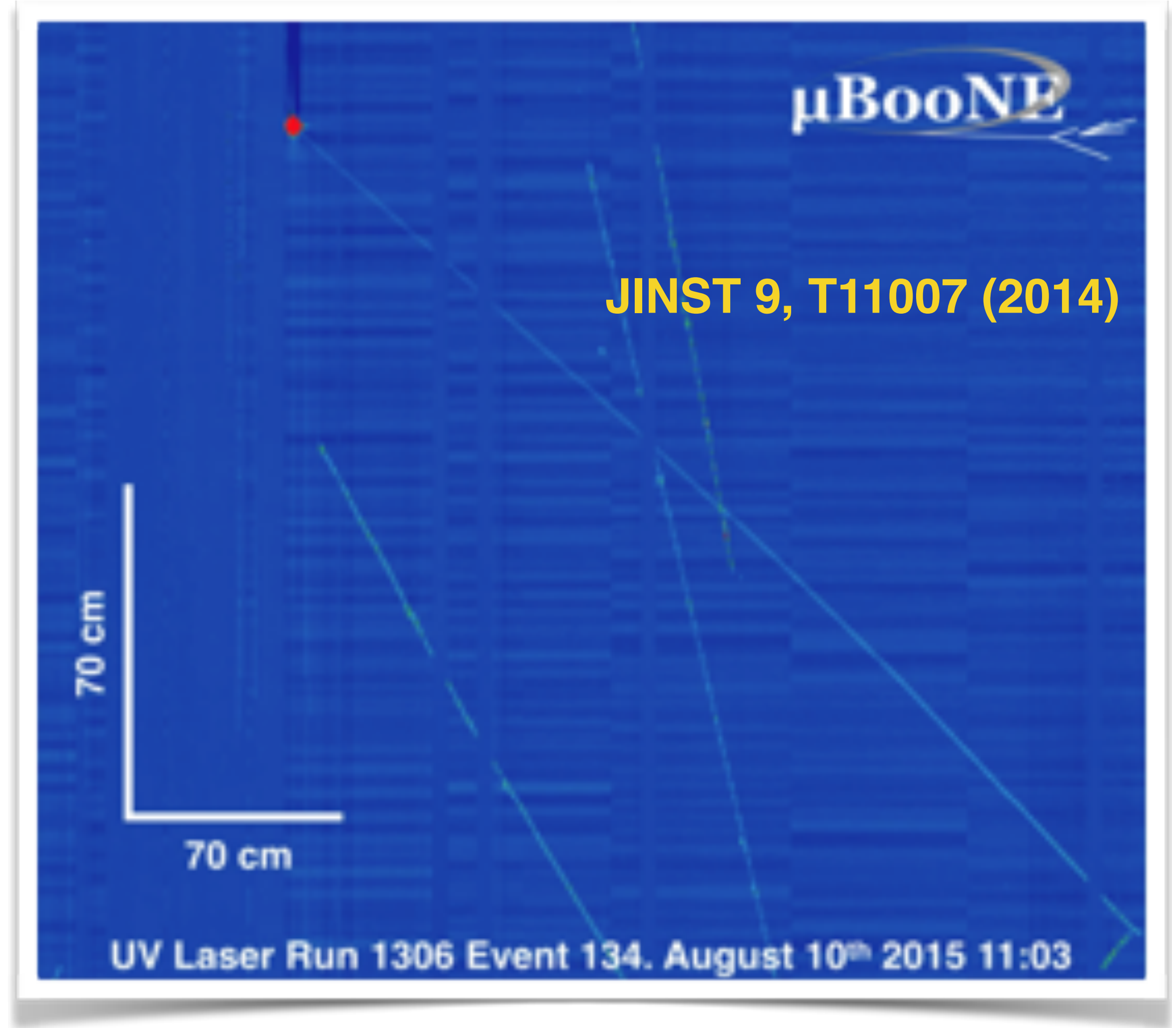
arXiv:1802.08709v2 (submitted to JINST)

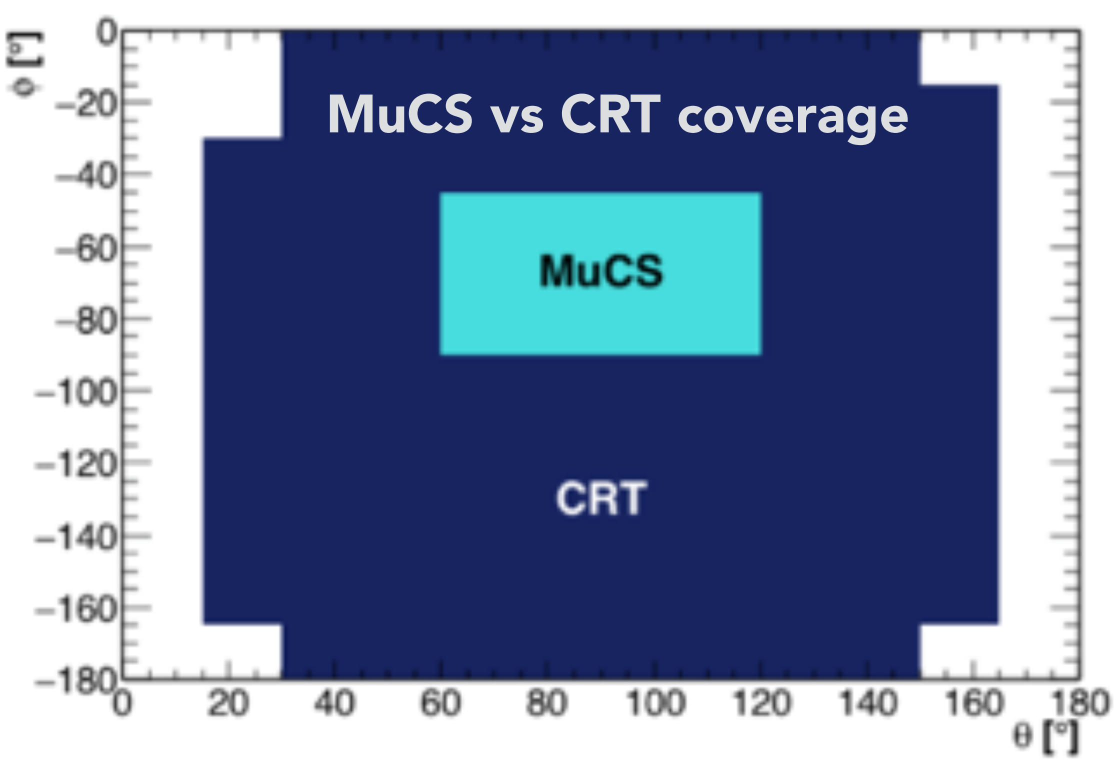


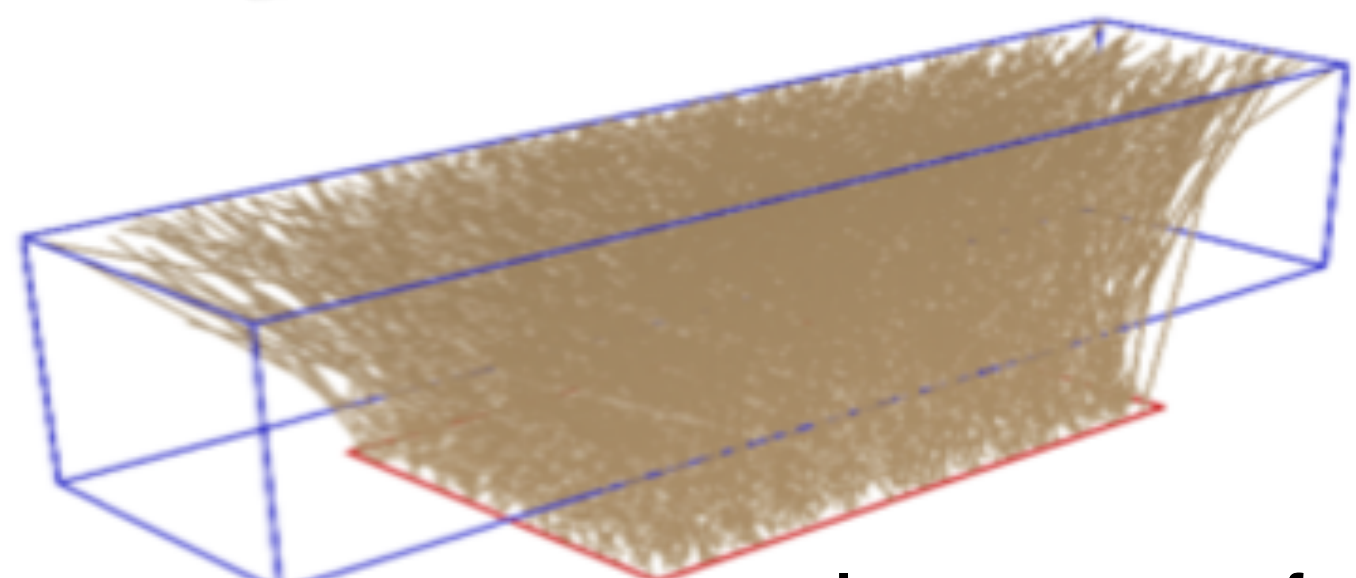
Neutrino Candidate event from MicroBooNE data

Space Charge Measurement Improvements

- Space Charge Measurement being improved combining various calibration sources
  - *UV Laser calibration data*
  - *Cosmic rays tagged using the larger CRT system*
- *Laser an ideal source to do 3D calibration for space charge*
- Also need to understand how liquid argon flow impacts ion movement

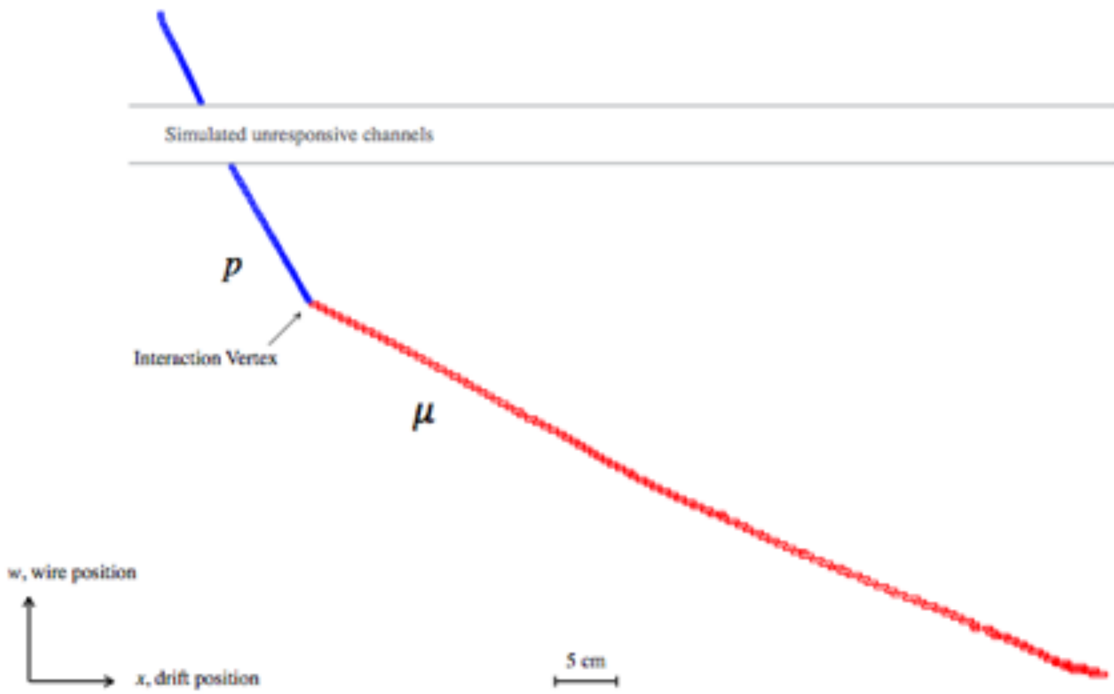




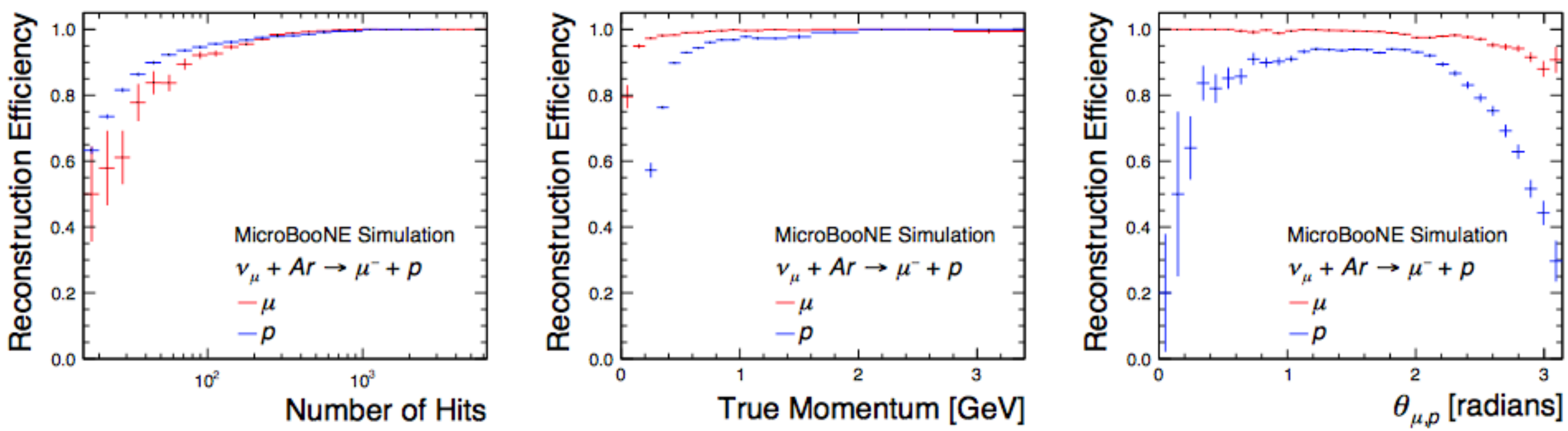


larger coverage of crossing muons from CRT

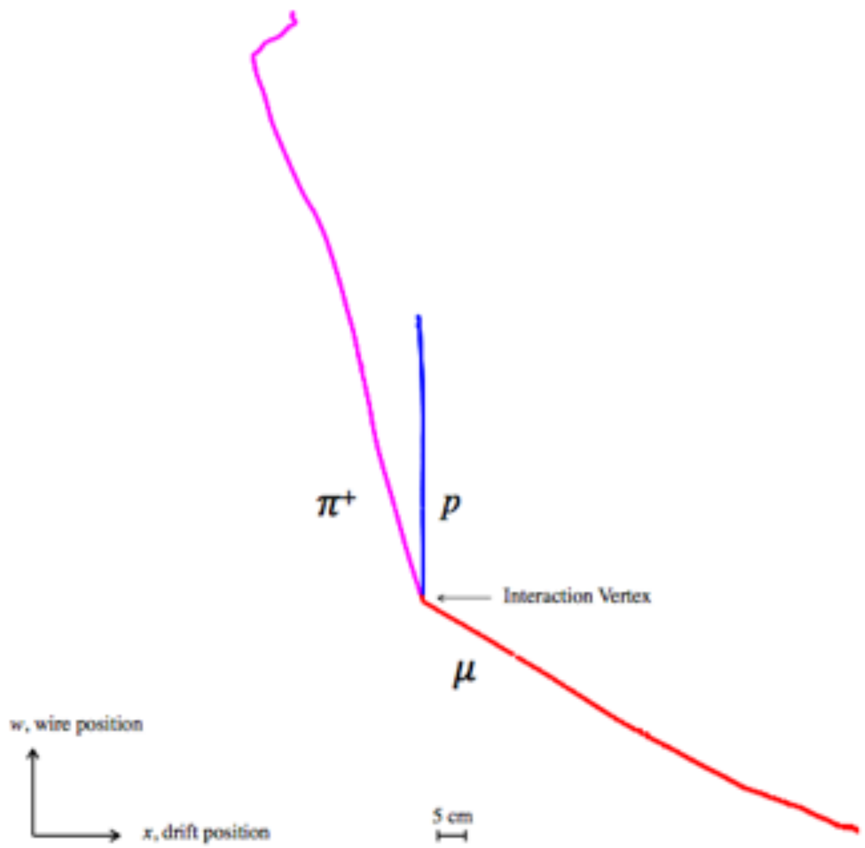
Pandora Reconstruction Performance



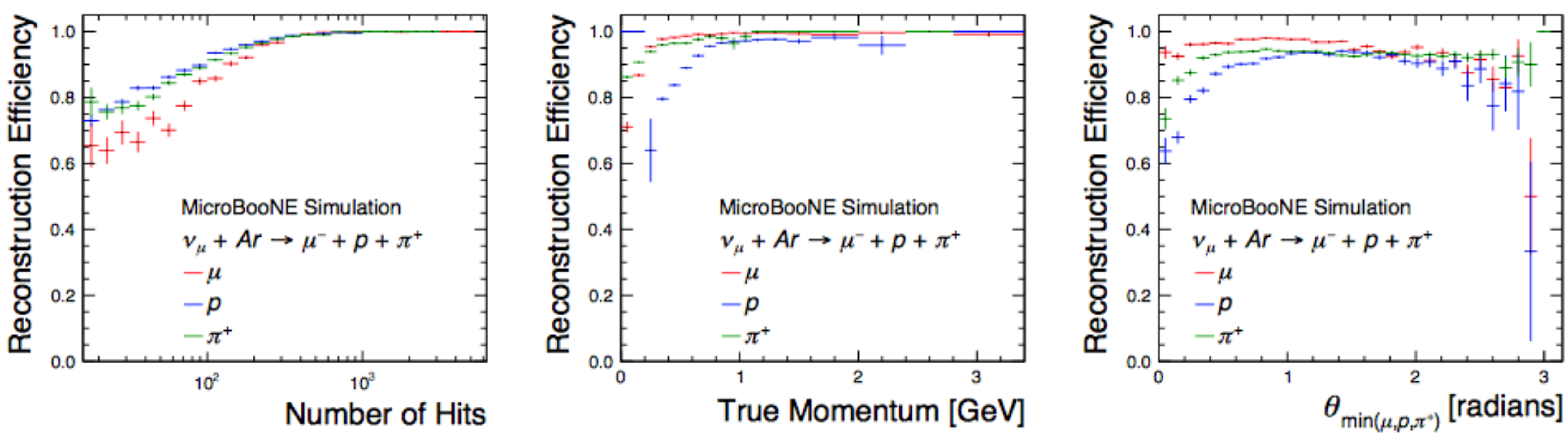
#Matched Particles	0	1	2	3+
μ	1.3%	95.8%	2.9%	0.1%
p	8.9%	87.3%	3.6%	0.2%



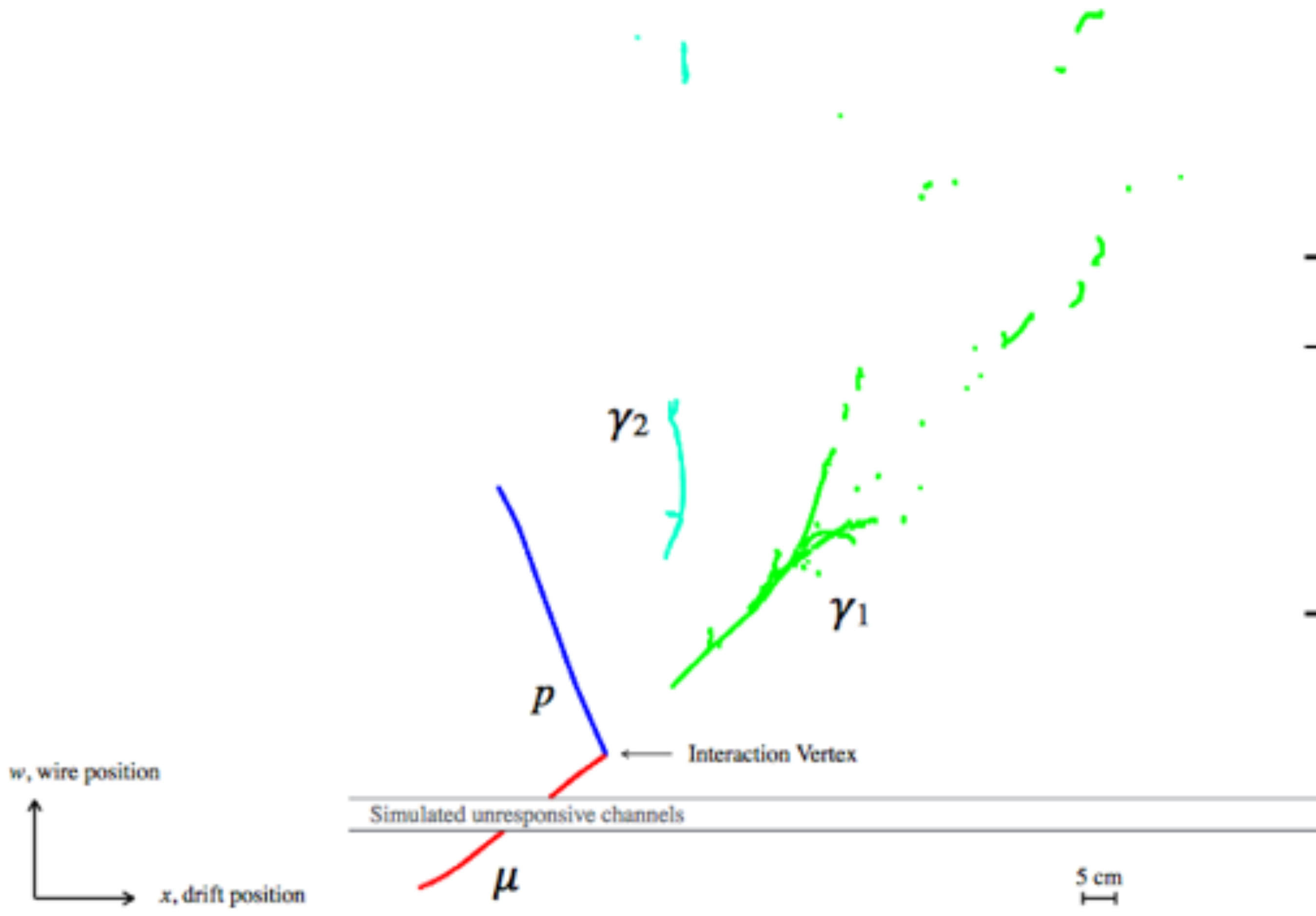
Pandora Reconstruction Performance



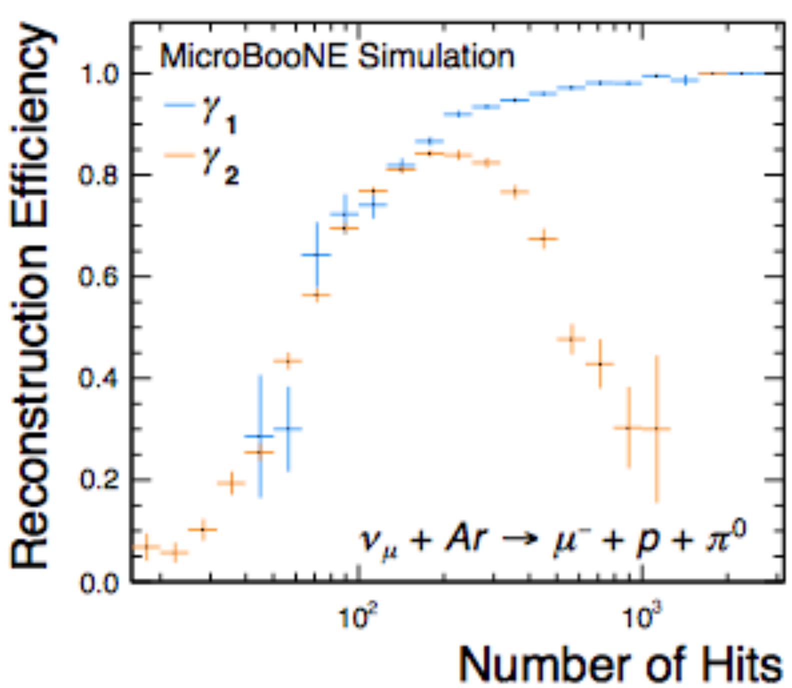
#Matched Particles	0	1	2	3+
μ	3.5%	95.1%	1.4%	0.0%
p	9.0%	86.8%	4.0%	0.3%
π^+	6.9%	80.9%	11.4%	0.8%

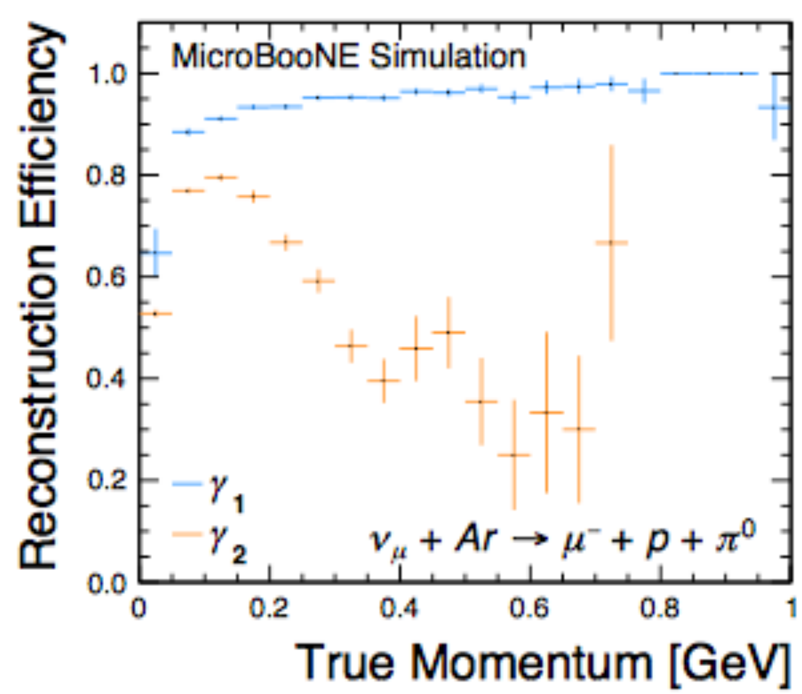


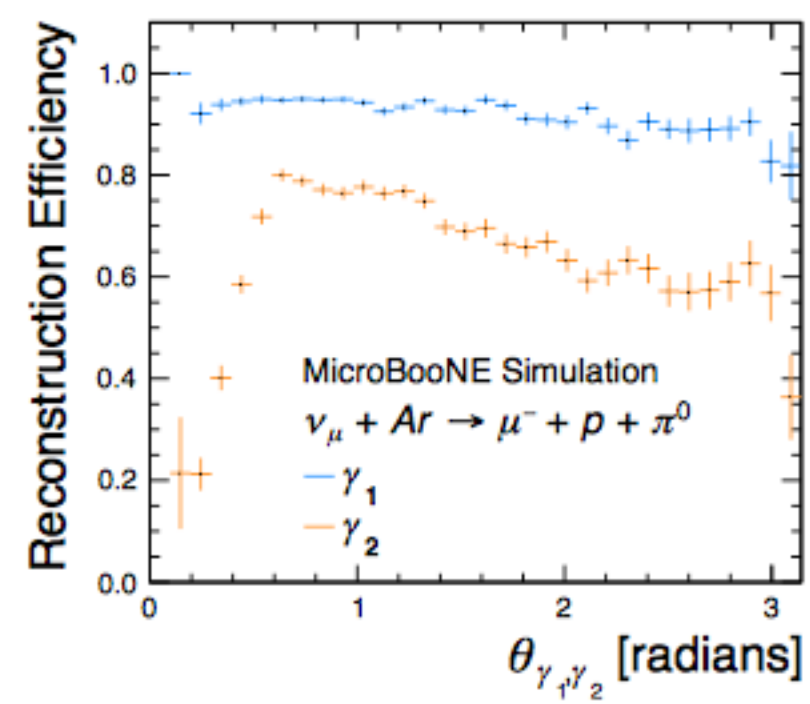
Pandora Reconstruction Performance



#Matched Particles	0	1	2	3+
μ	3.7%	94.8%	1.5%	0.0%
p	9.9%	85.5%	4.3%	0.3%
γ_1	6.8%	88.0%	4.8%	0.4%
γ_2	29.9%	66.4%	3.6%	0.2%







Proton decay background

Some GUT models explicitly break the baryon number symmetry predicting proton decay

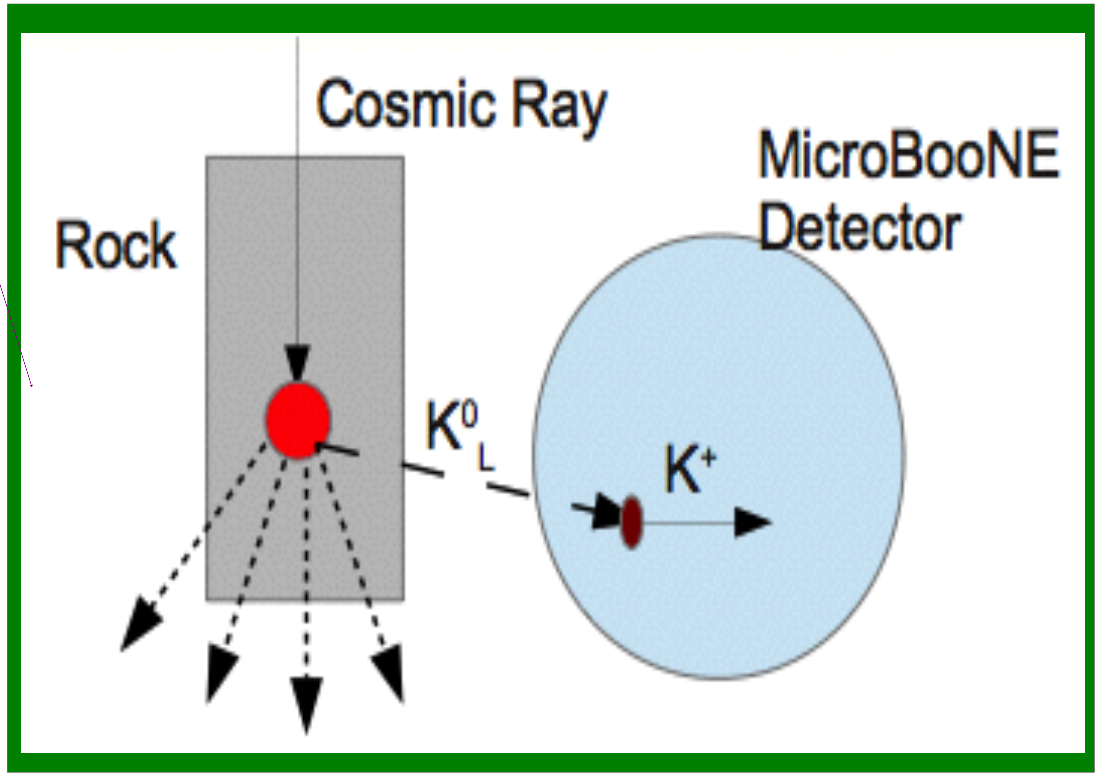
MicroBooNE is not big enough to study proton decay itself

– *But, MicroBooNE can study proton decay backgrounds for future experiments!*

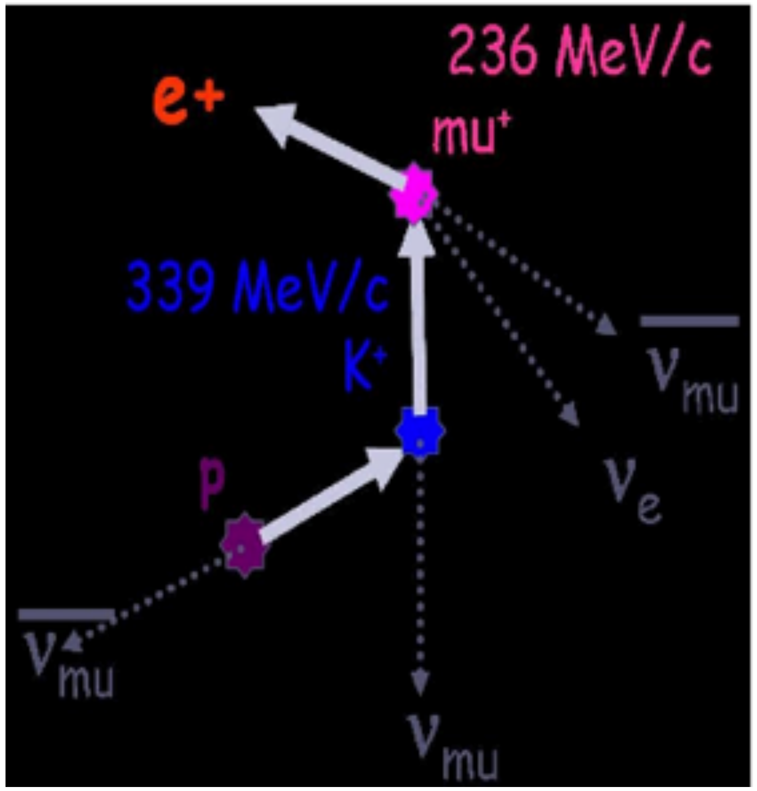
Proton decay background
A cosmic muon interacts in a rock near the detector, produces a K^0_L which then charge exchanges, $K^0_L p \rightarrow K^+ n$ = looks like a K^+ from proton decay if right energy (339 MeV/c).

Decay mode of interest to MicroBooNE: $p \rightarrow K^+\nu;\ K^+ \rightarrow \mu^+\nu_\mu;\ \mu^+ \rightarrow e^+\nu_e\,(\text{anti-}\nu_\mu)$

– the distinct dE/dx pattern enables study of this 3-fold decay mode

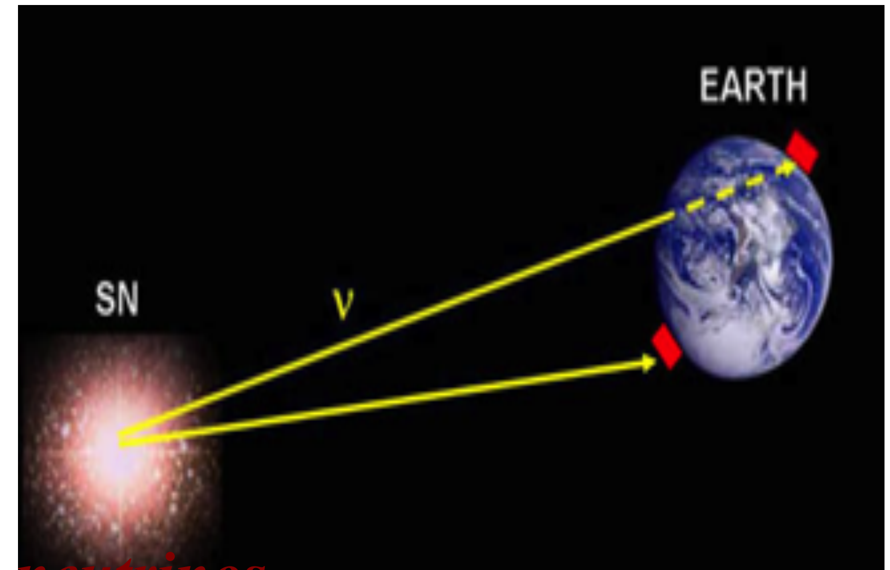


From J. Esquivel



Supernovae neutrinos

A core-collapse supernova **(SN)** produces **a burst of neutrinos of all flavors (in few-tens-of-MeV range)**
→ physics of oscillations of SN neutrinos holds key astronomical phenomena



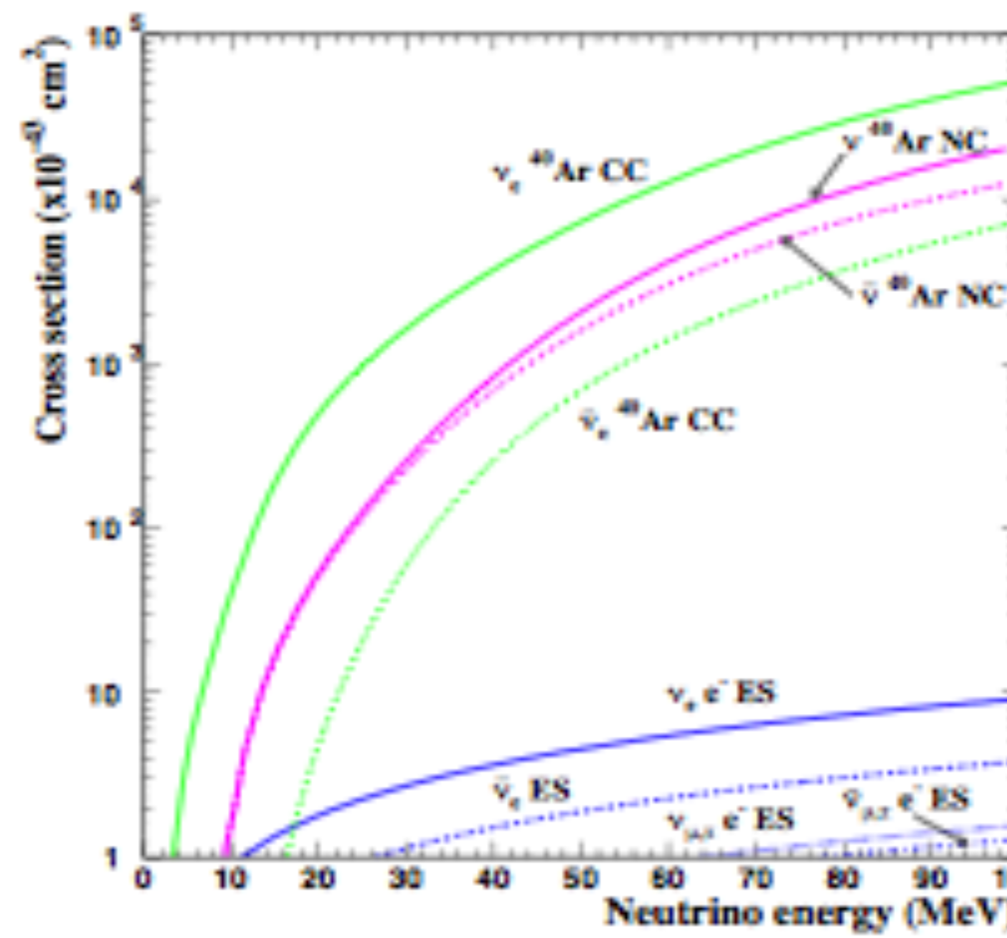
Water and liquid scintillator neutrino detectors,
→ **primarily sensitive to electron anti-neutrinos**
anti- $\boldsymbol{\nu_e + p \rightarrow n + e^+}$ *(inverse beta decay on free protons)*

LArTPCs posses unique capability to detect SN *electron neutrinos*

1. CCν_e capture of SN neutrinos on Ar
   $\nu_e + Ar^{40}(18) \rightarrow K^{40}(19) + e^-$

Other processes:
2. Neutral current excitation of Ar^{40}
   $\nu_{e,\mu,\tau} + Ar^{40}(18) \rightarrow Ar^{*40}(18) + \nu_{e,\mu,\tau}$

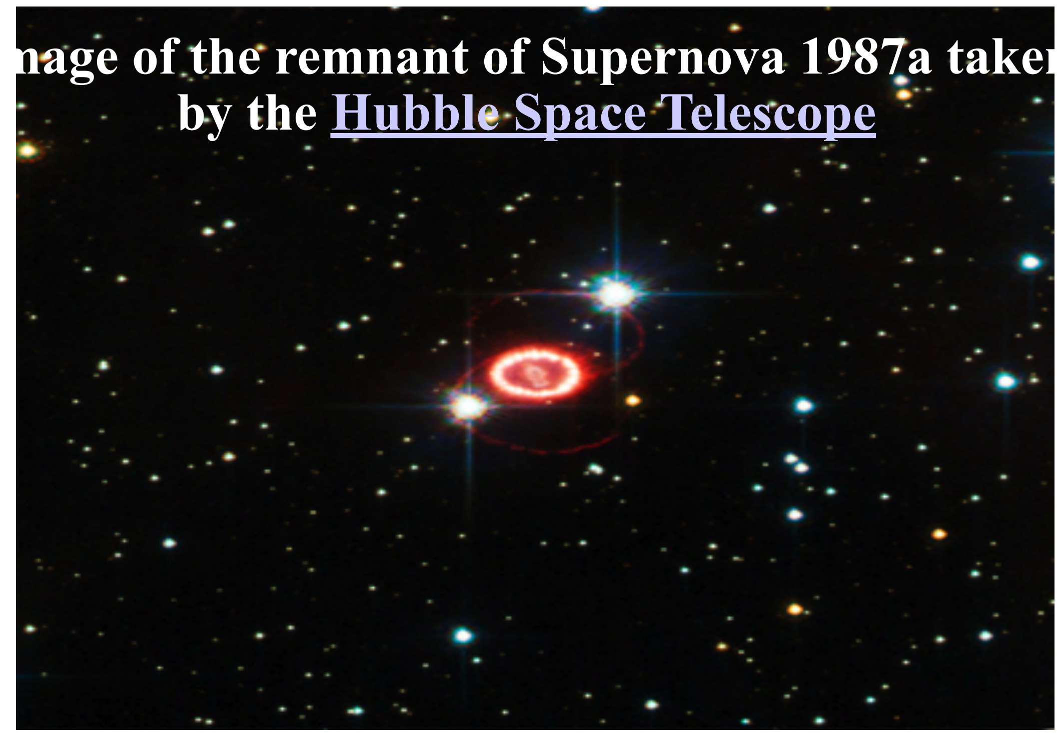
3. Elastic scattering off electron
   $\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$



Supernovae neutrinos

Detection requires sensitivity to low-energy gammas (<50 MeV) and electrons

- $CC\nu_e$ capture on Ar can be tagged via the coincidence of emitted electron and accompanying de-excitation gamma cascade



Due to small size of MicroBooNE,

- will only see about *10-20 SN neutrinos in a duration of about 20 seconds*
- A multi-kiloton detector (like LBNE) will be able to see a few hundred SN events!

SNEWS

Supernova Early Warning System

Triggering on Supernovae events,

- MicroBooNE sits just below surface, *too much cosmic traffic to have its own trigger!*
- MicroBooNE will subscribe to SNEWS!