Recent MicroBooNE Results

Andy Furmanski

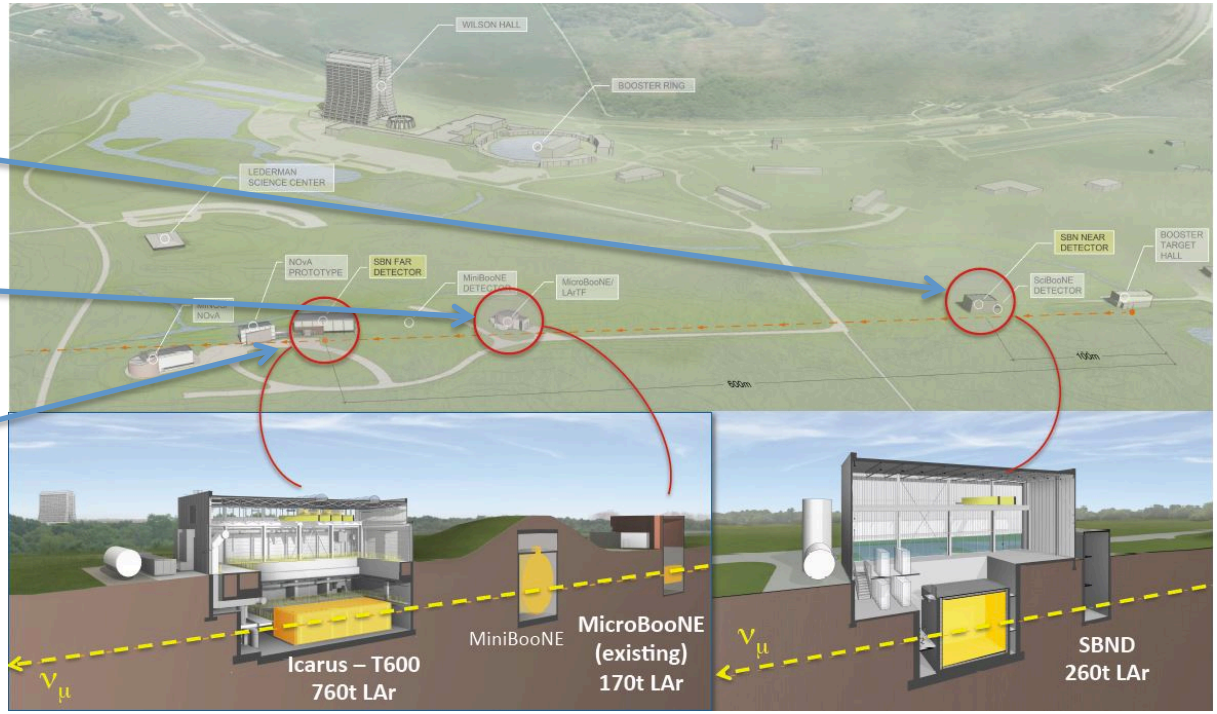
NOW2016

7th September 2016

Fermilab Short Baseline Programme

- Unprecedented sensitivity to eV-scale sterile neutrino oscillations
  - In both appearance and disappearance channels

Detector	Distance	Argon mass
SBND	110 m	260 t
MicroBooNE	470 m	170 t
ICARUS	600 m	760 t



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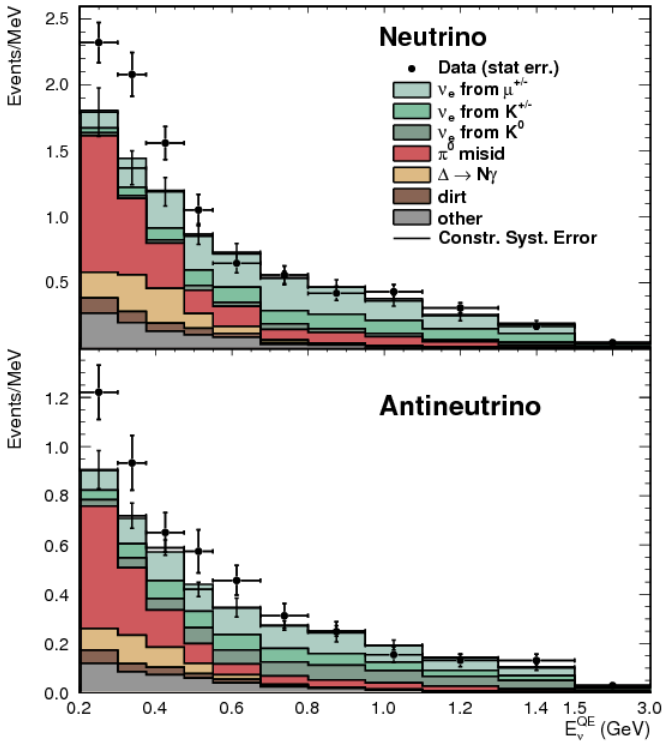
A short history of **Mini**BooNE

- **Mini**BooNE was designed to search for ν_e appearance in a ν_μ beam
  - At short distances –> eV-scale sterile oscillations
- **Mini**BooNE saw an excess of electron-like events at low energies
- **Mini**BooNE had almost no separation between electrons and photons



Why MicroBooNE?

- Liquid argon TPC is a very different detector technology to mineral oil Cerenkov
- Fine-grained tracking reveals more about the neutrino interaction
  - Low-energy particles?
- Vertex separation and dE/dx provide electron/photon separation

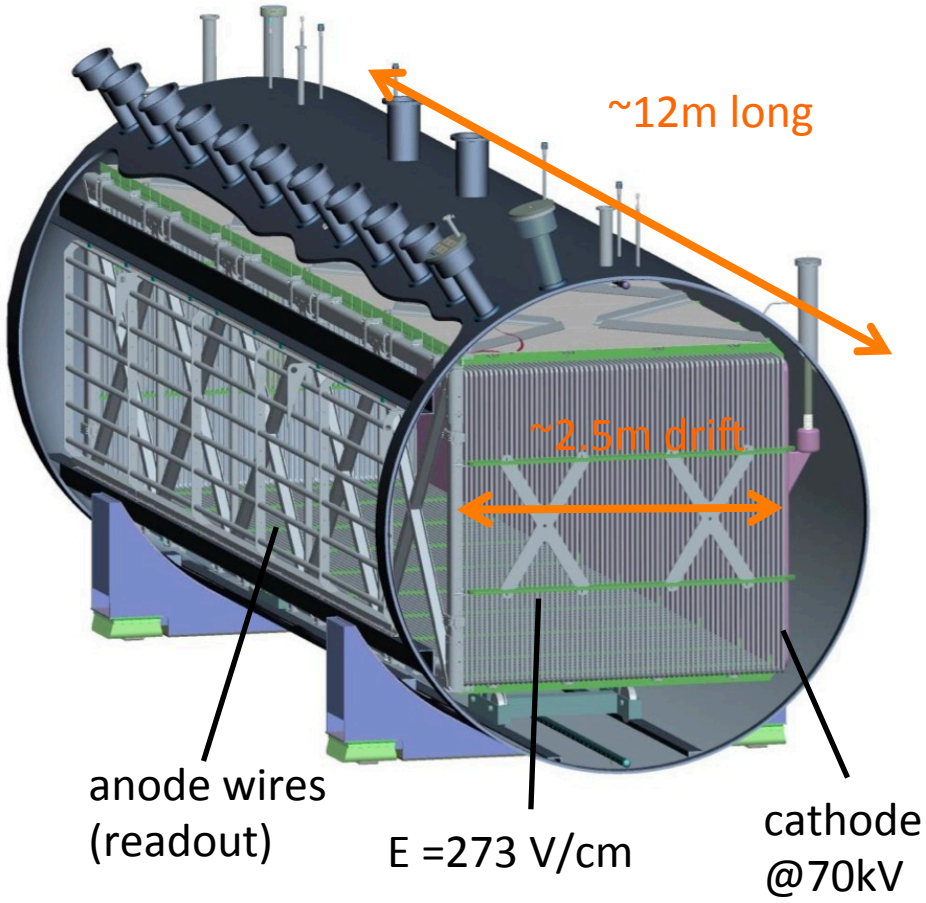
MicroBooNE

- MicroBooNE is the first detector in the SBN programme
- It will run for 3 years by itself before being joined by SBND and ICARUS

- Main goals of the 3-year run:
  - Investigate MiniBooNE low energy excess
  - Study/measure neutrino cross sections on argon
  - Demonstrate liquid argon technology required for DUNE (cold electronics, argon purity, etc)

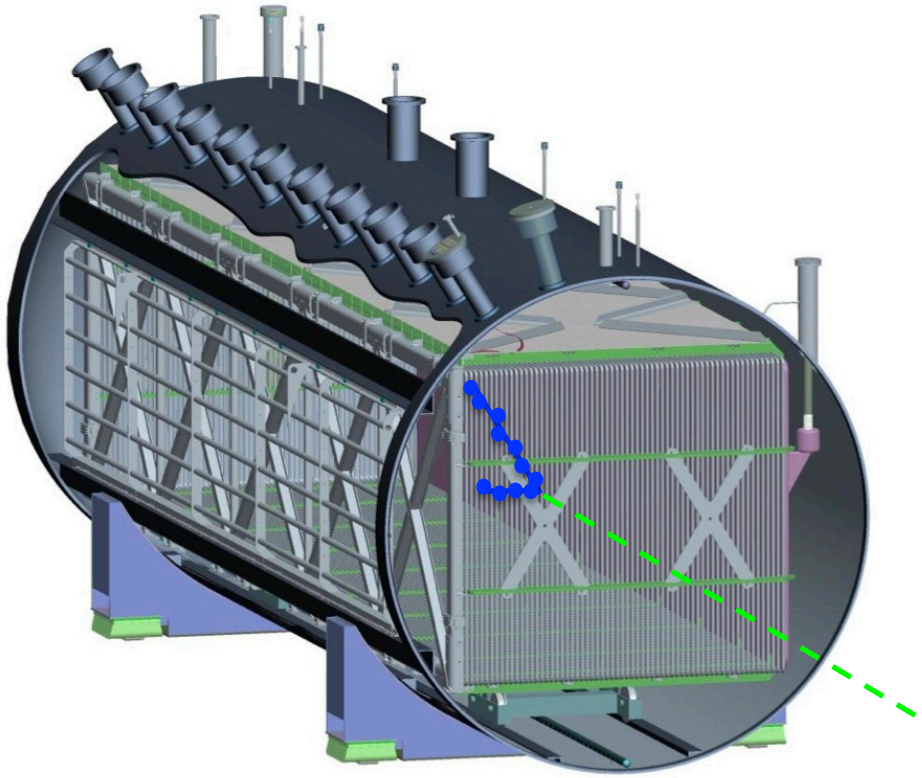
The detector

- 170 tons of liquid argon
- Cylindrical cryostat
- Rectangular TPC inserted
  - Contains ~90 tons of liquid argon
- Passive insulation



The (charge) detector

- Particles ionise argon atoms
- Free electrons drift in high electric field to the wire planes



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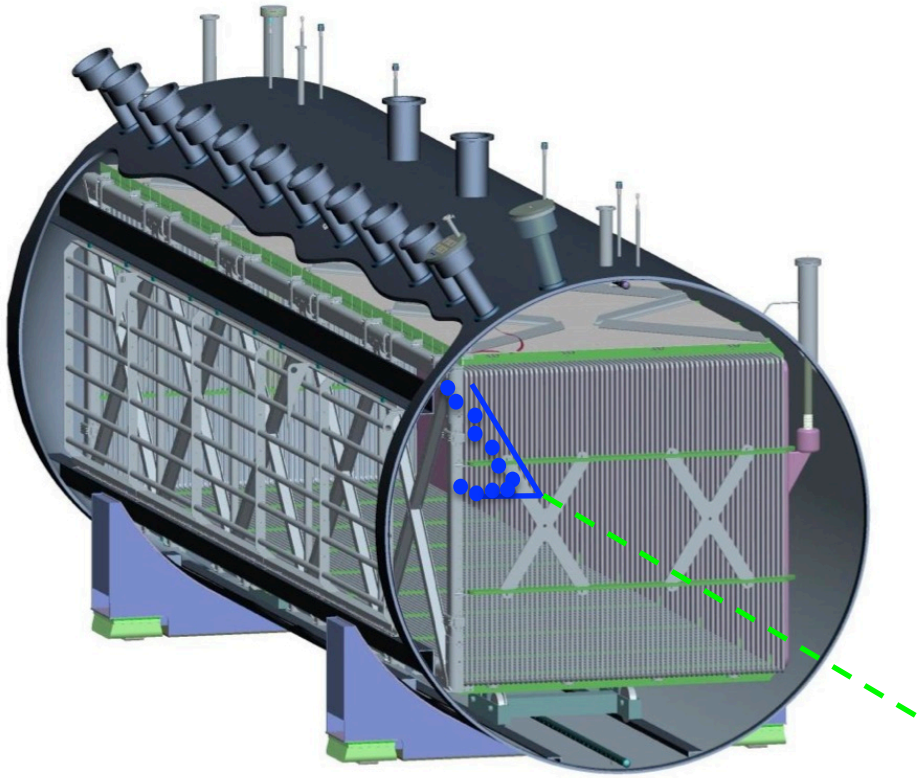
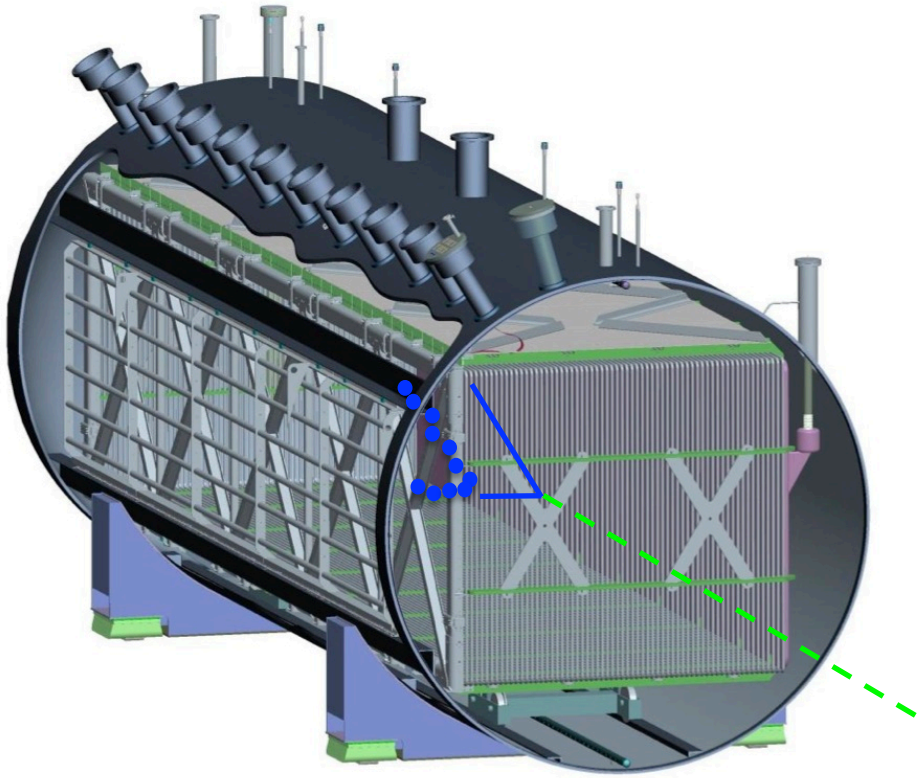


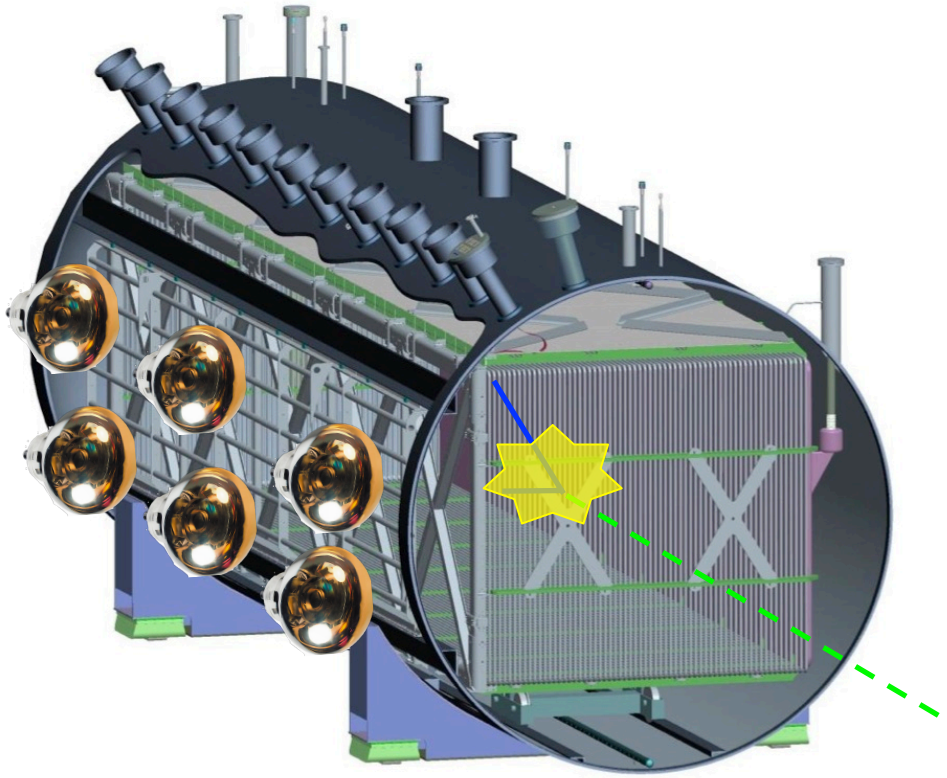
The (charge) detector

- Particles ionise argon atoms
- Free electrons drift in high electric field to the wire planes
- Induce signals on the wire planes



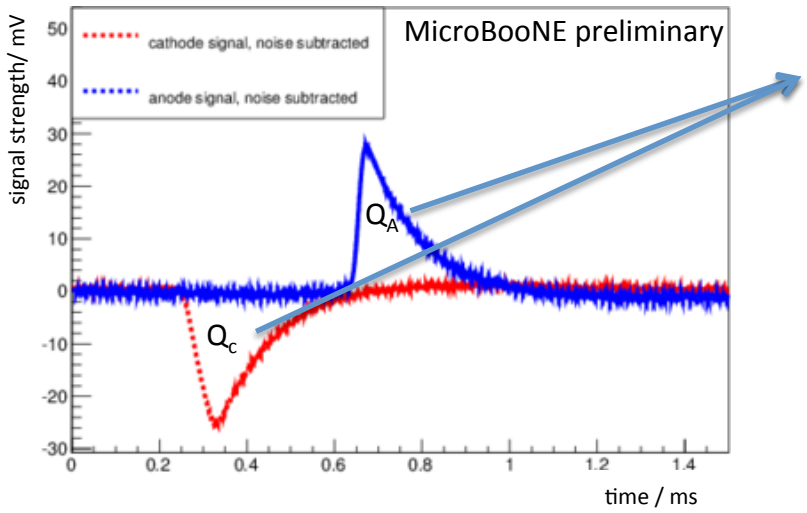
The (light) detector

- 32 eight-inch PMTs
- Placed behind the anode wires
- Reconstruct flashes from scintillation light
- Determine tracks t_0 from flash time

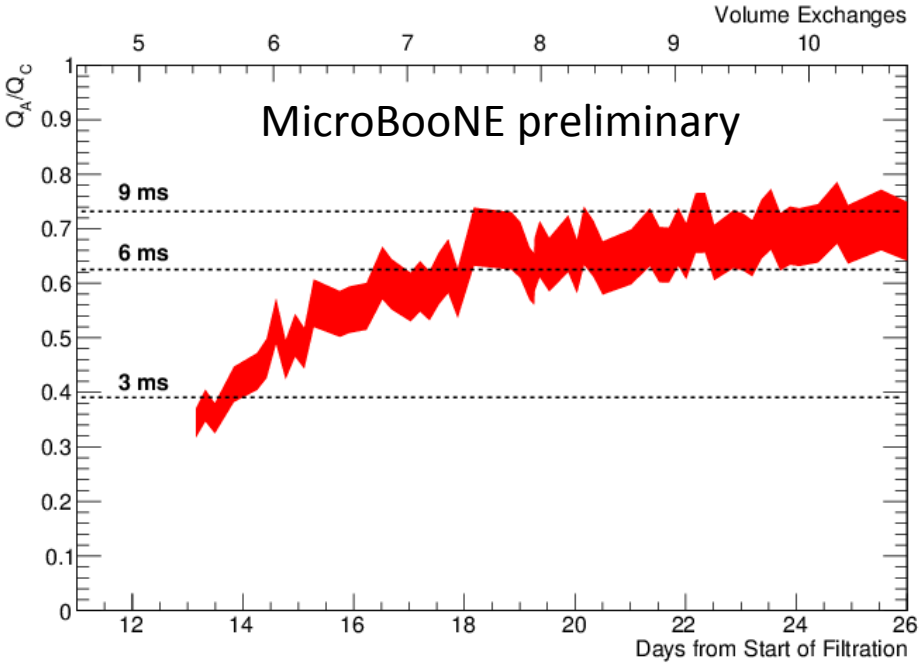


Argon purity

- For free electrons to survive the drift distance the free electron lifetime needs to be >3ms
  - This requires very pure argon!
  - We have achieved >9ms electron lifetime!
  - (and kept it there)

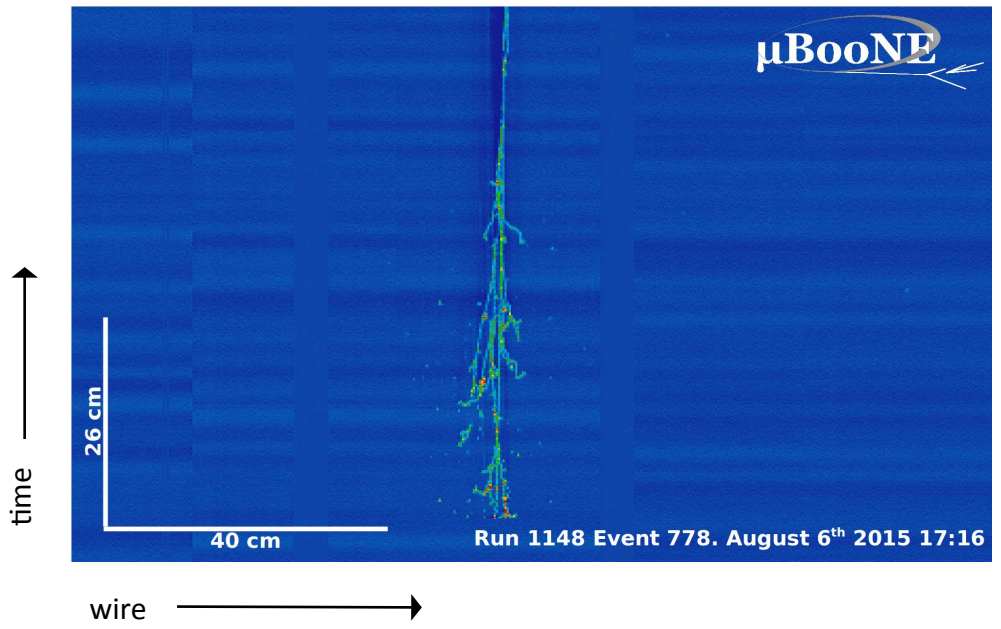


Q_A/Q_C = fraction of charge that survives drift time



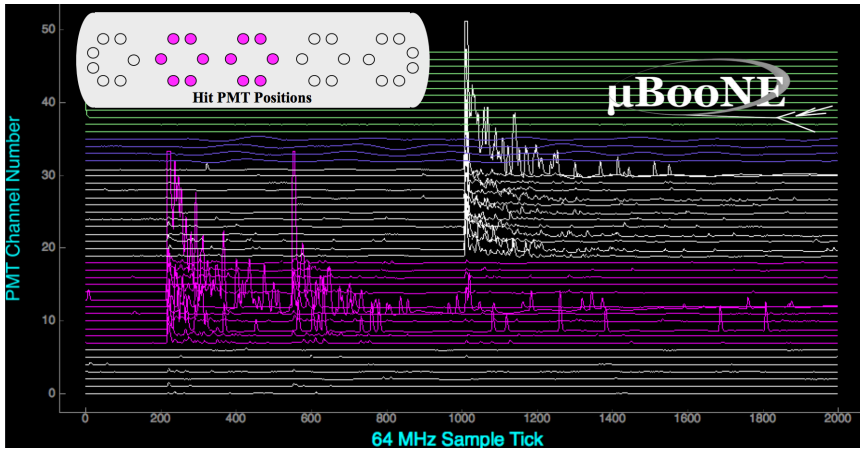
MicroBooNE event display

- Cosmic tracks seen in MicroBooNE shortly after turning the drift field on!
- Very detailed images of showers!
  - Millimetre scale resolution



Optical signals

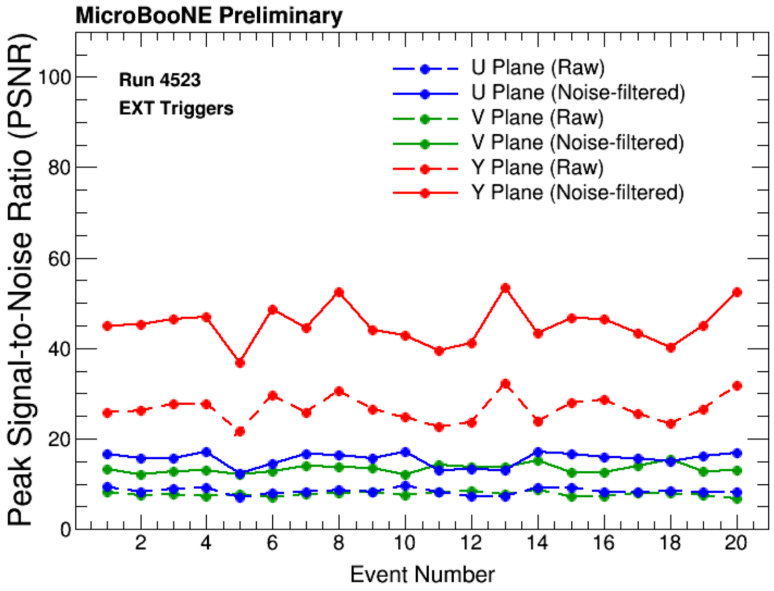
- **Pulses identified** in PMT waveforms **to form hits**
- Hits close together in time and space are **grouped into flashes**

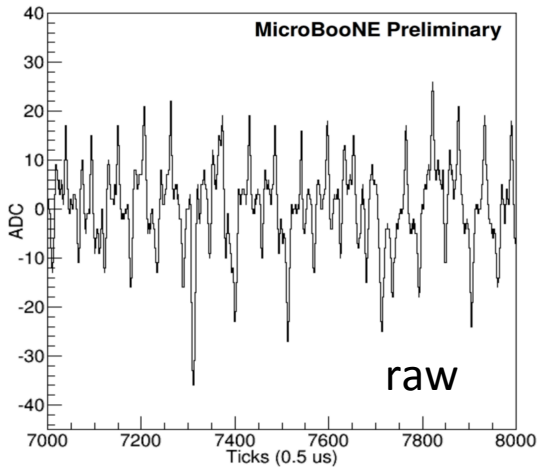


- Flashes characterised by amplitude, time, and location
- Small flashes are very common, large flashes are usually caused by cosmic muons, cosmic showers, or beam interactions

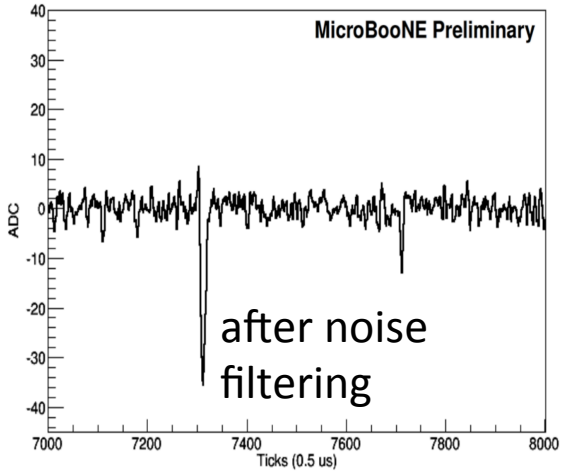
TPC signals

- TPC signals meet or beat design noise targets
- Many noise sources can be filtered out offline
  - Or could be filtered in hardware
- Remaining noise is <400 ENC – best in a LArTPC ever!





signal processing

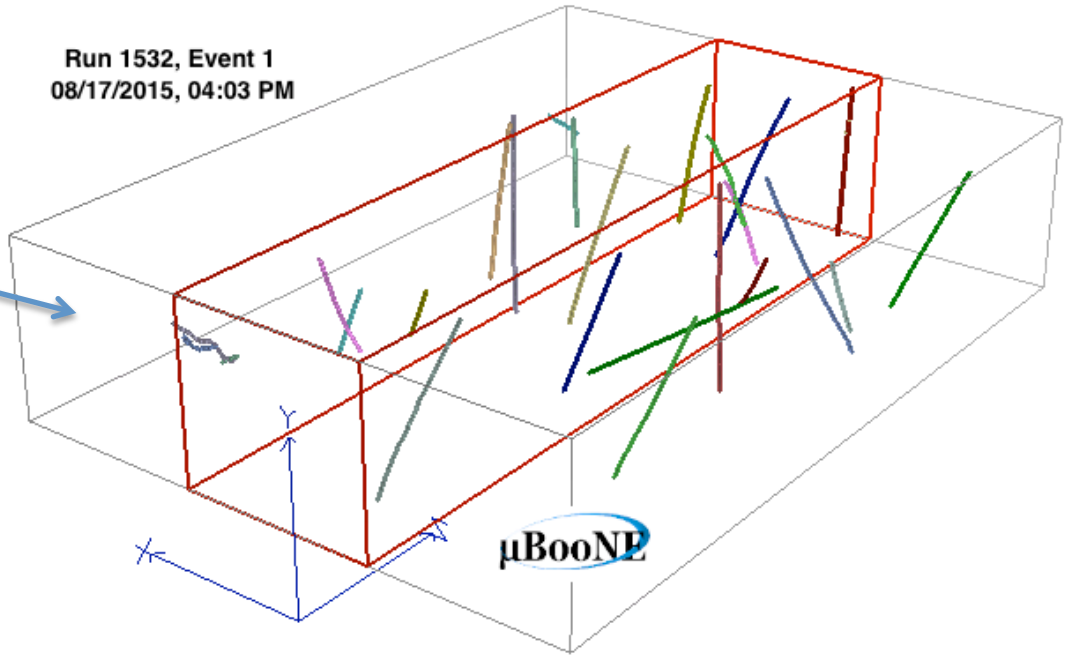


TPC reconstruction

- For each wire plane, signals are noise-filtered, deconvolved, and calibrated
  - Produces gaussian-like hits in all planes
- Clustering algorithms group nearby hits that likely originate from the same particle
- 3D reconstruction matches between planes
  - Based on time and wire-intersections
- Produces 3D tracks and vertices

Cosmic tracks

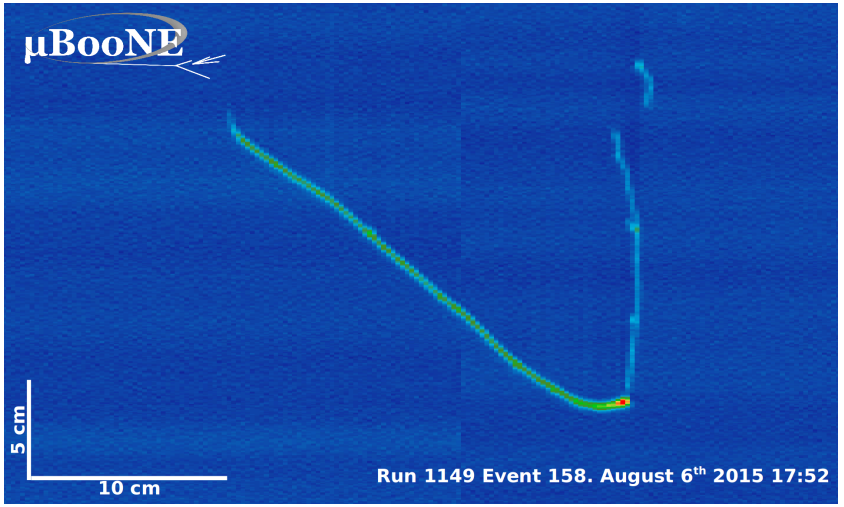
- In every event, there are many cosmic muons visible
- Long drift time + surface detector!
- Reconstructed tracks in a single data event



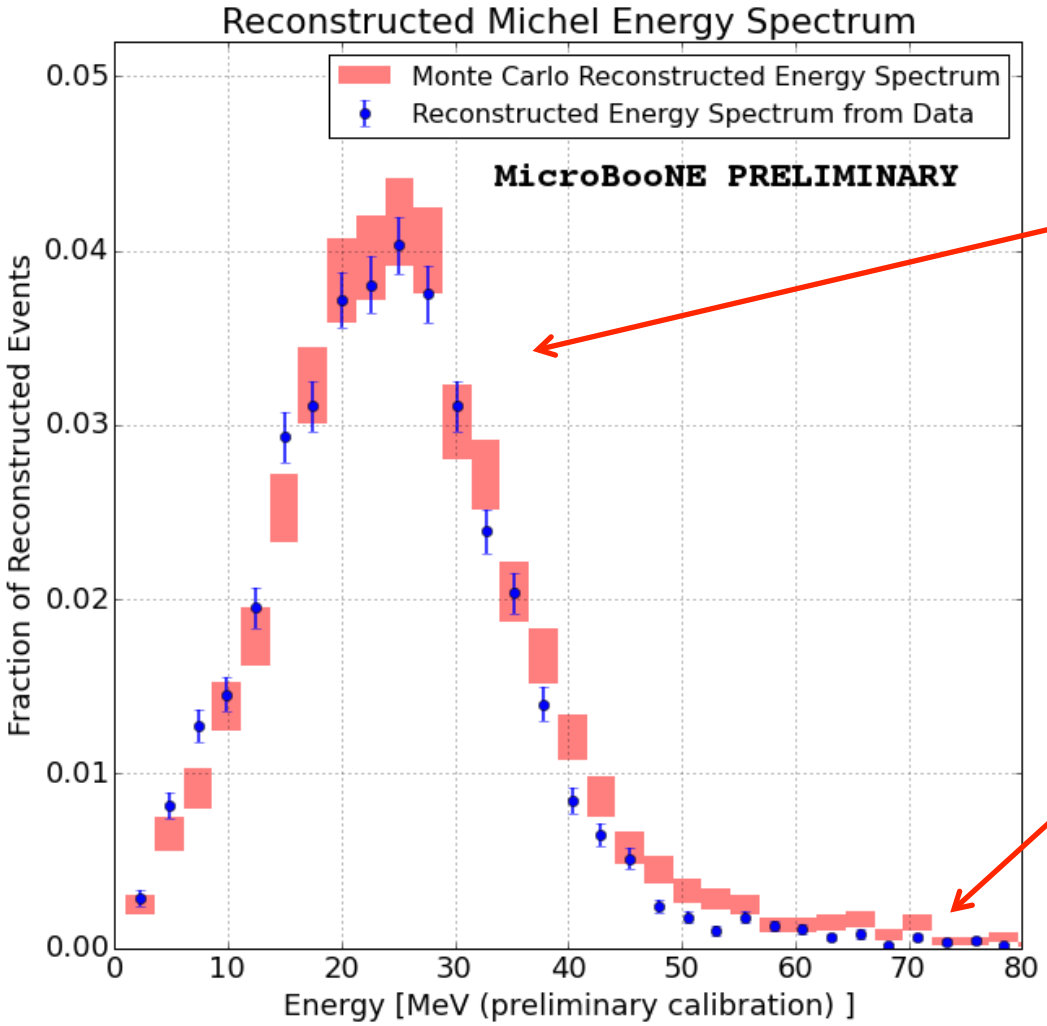
Finding Michel electrons

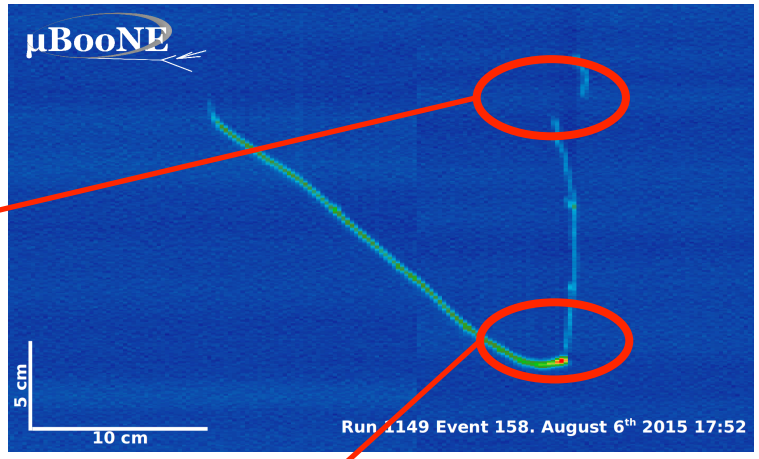
- Find stopping-and-decaying cosmic muons in MicroBooNE
- Test **reconstruction**, **calorimetry**, of low-energy electrons
- Sample very relevant for understanding supernova neutrinos!

- Look for hard ‘kink’
- Look for muon Bragg peak



Michel energy spectrum





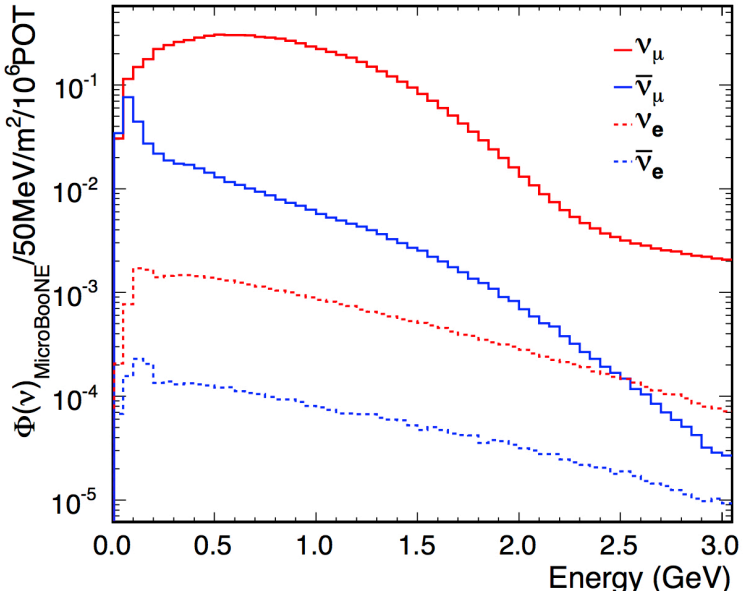
Peak shifted down – some charge lost due to radiative losses which is difficult to cluster

High tail – accidentally pull in some charge deposited by the muon Bragg peak

The Booster Neutrino Beam

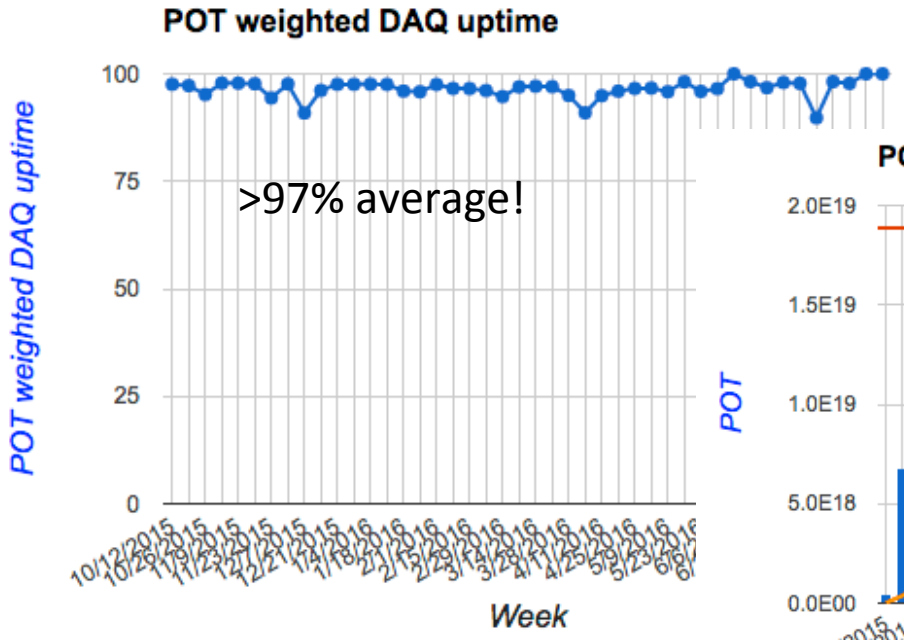
- 8 GeV protons taken from the booster accelerator
- Hit a Beryllium target
  - Produces a spray of mainly pions, some kaons
- A single focusing horn focuses the right-sign pions

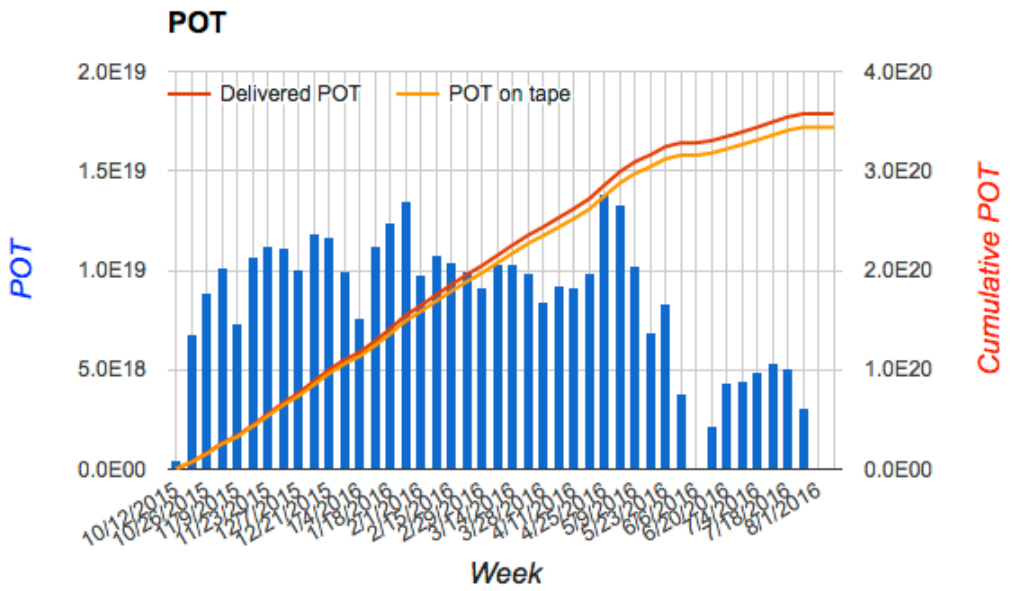
- On-axis flux peaks at around 600 MeV
- Wide-band beam
- Very low wrong-sign background



Beam!

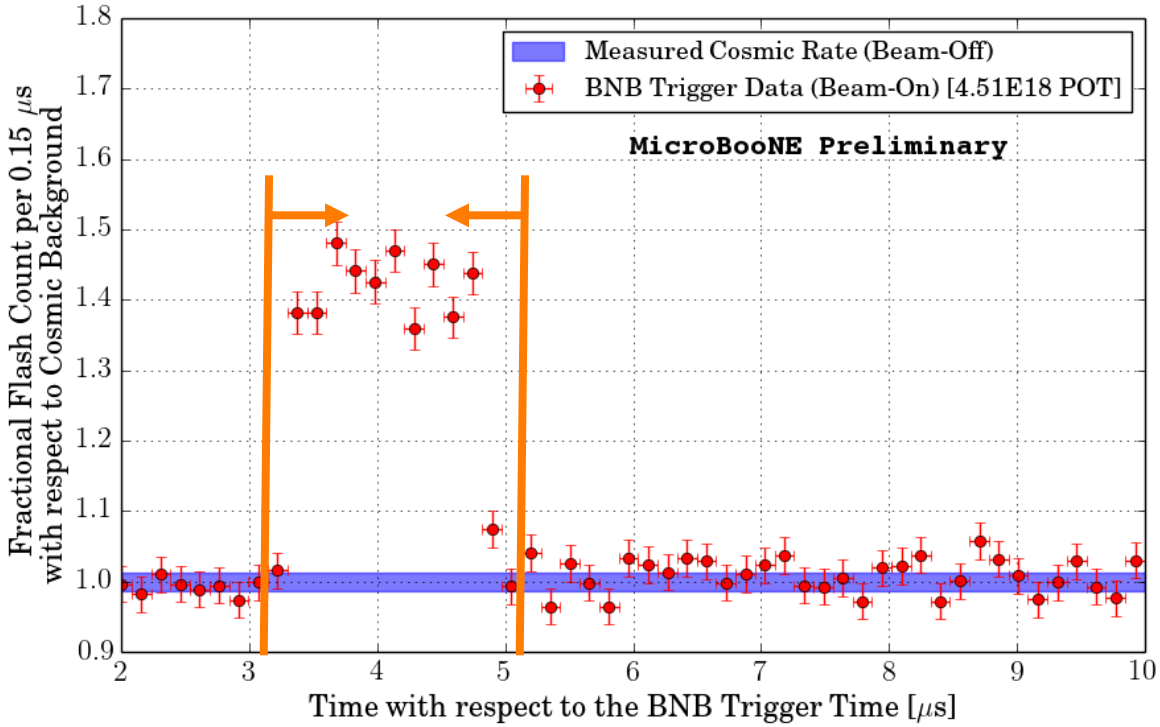
- The BNB was turned on in October 2015
- Beam ran extremely well
  - Beam turned off in August after delivering 3.57e20 POT!





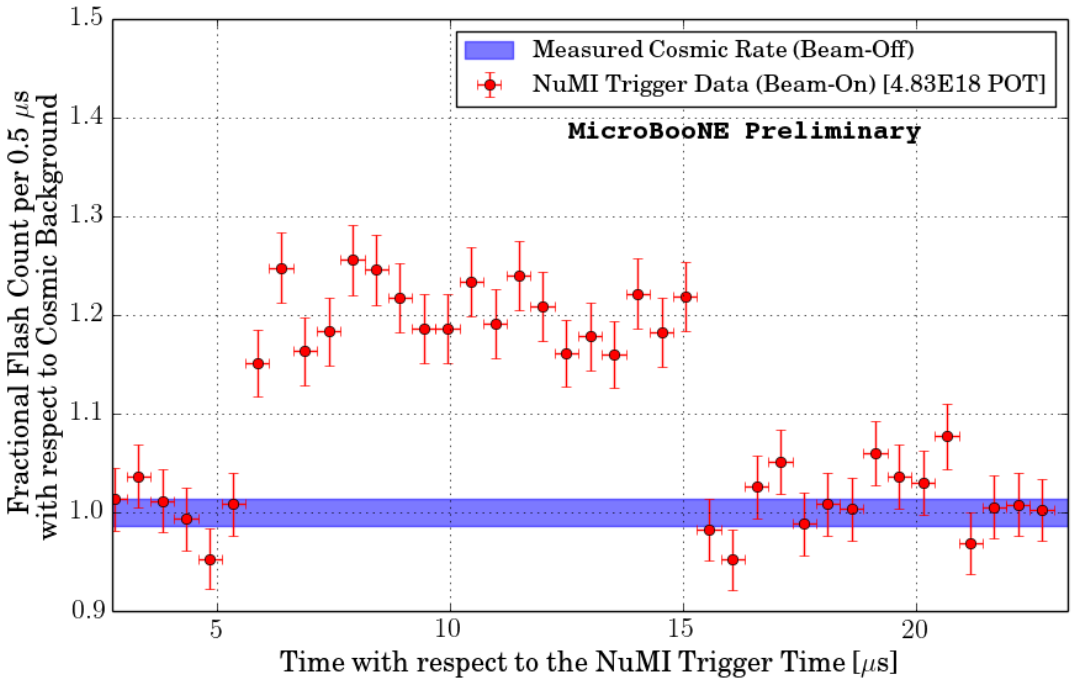
Neutrino peak

- Distribution of flashes over 50 PE
- Excess at the right place, and the right width

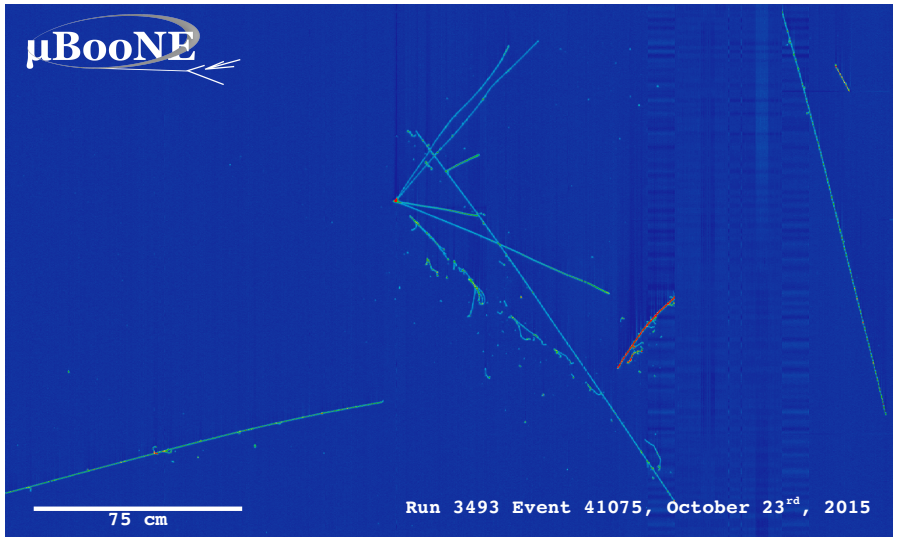


NuMI peak

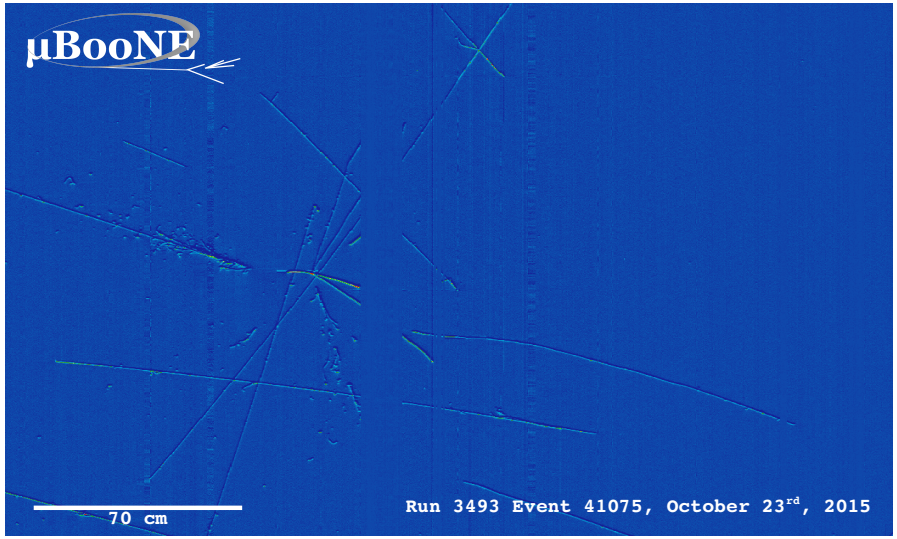
- MicroBooNE is also exposed to the NuMI beam
- MicroBooNE is very off-axis
- Allows us to study an alternative flux

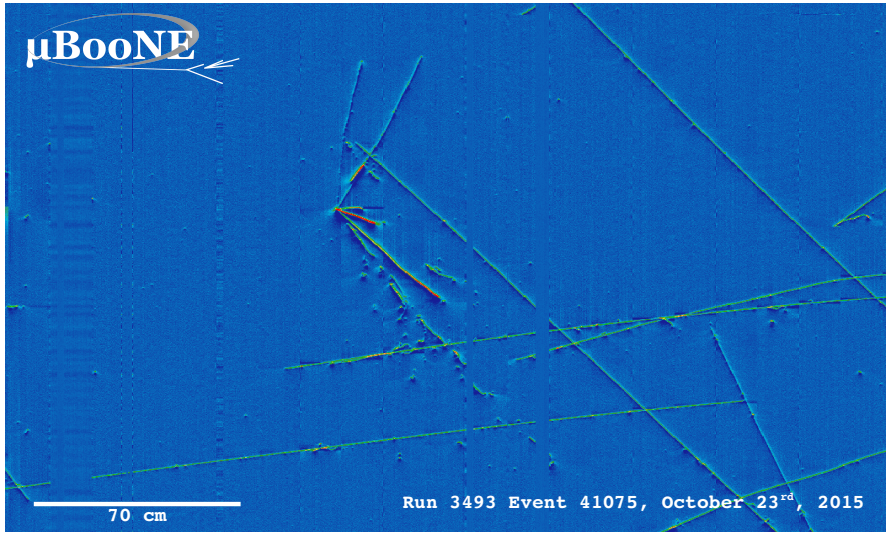


Neutrinos!



- Requiring a flash in time with the beam and some **simple cuts**
- Neutrino candidates found with **fully automated reconstruction**
- All three planes working well (**same event** shown in **3 views**)





Working towards a low-energy excess

How do you check MiniBooNE with MicroBooNE?

Cosmic muons:
- Track reconstruction
- Recombination, diffusion, lifetime
- Space charge effects
- wire-to-wire calibration

Cosmic Michel electrons:
- Shower reconstruction (low E)
- Calorimetry

Cosmic samples

Beam samples

ν_μ CC-inclusive:
- (Flux) x (cross section)
- Intrinsic ν_e constraint

ν_μ CC-π^0, NCπ^0:
- Shower reconstruction (higher E)
- Calorimetry
- π^0 background constraint

Detector physics

Off-beam physics

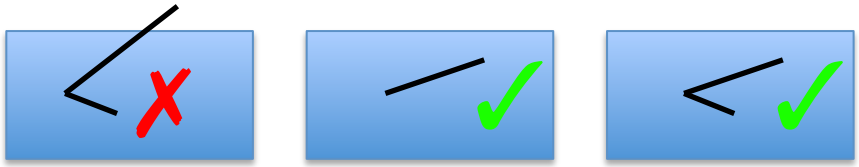
Low energy excess search

Cross section measurements

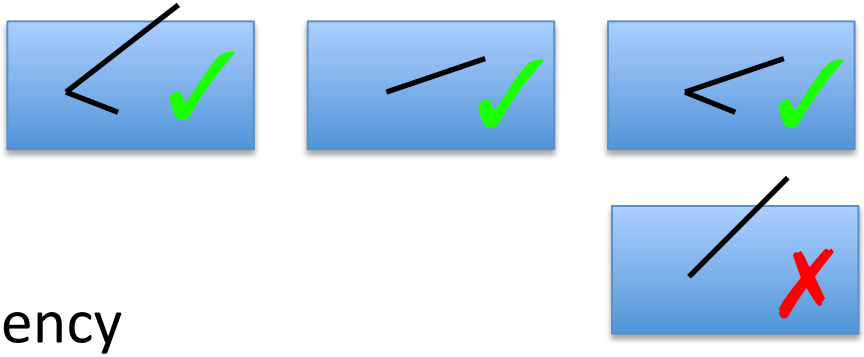
CC-inclusive event selection(s)

- Two selections developed

- **Selection I:**
  - Fully contained
  - Intended to be simple

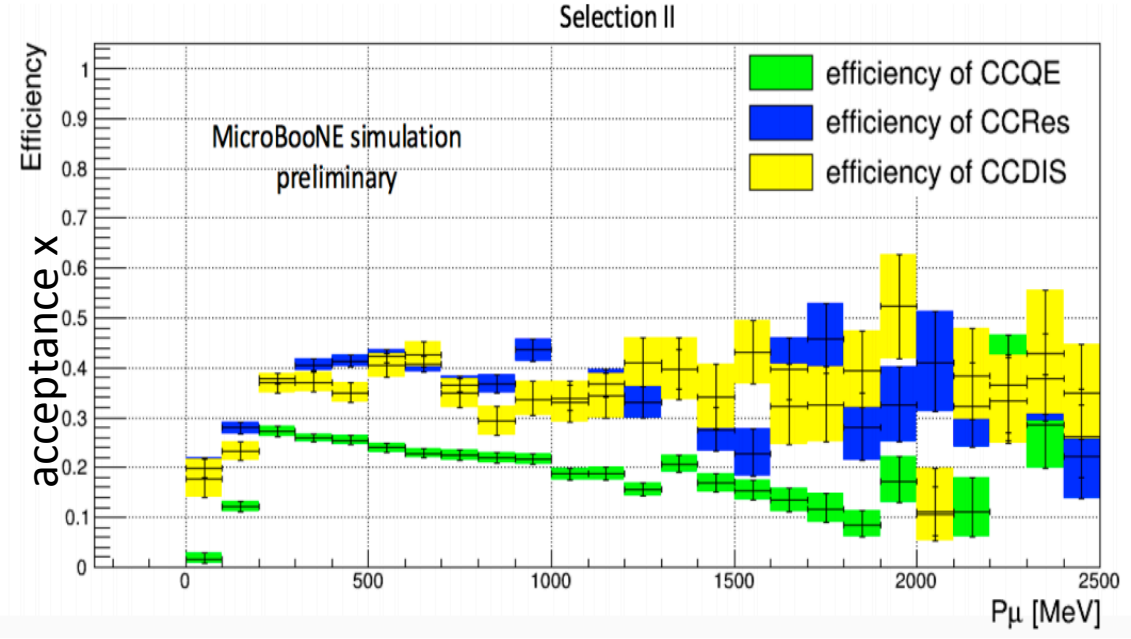


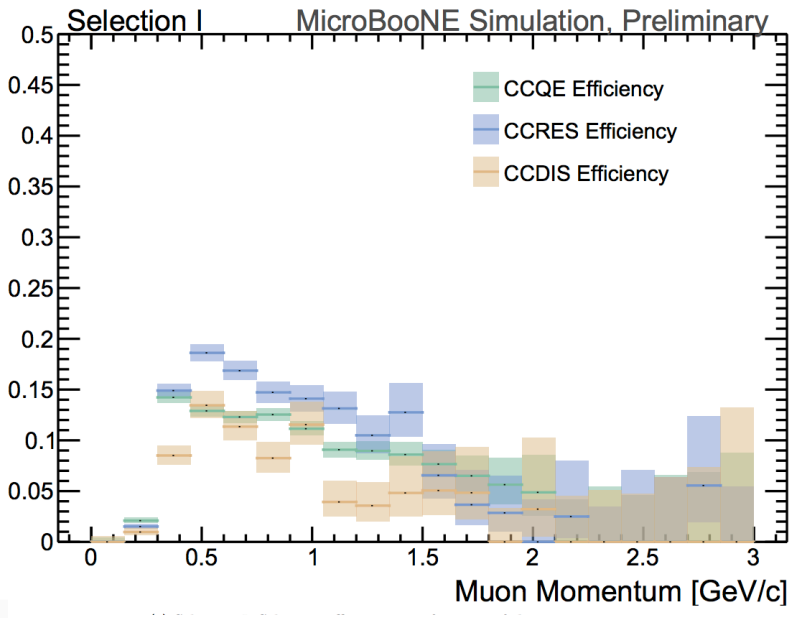
- **Selection II:**
  - Single-track contained
  - Multi-track contained
  - Multi-track uncontained
  - Intended to increase efficiency



- Both start with a **>50PE flash** within the beam spill

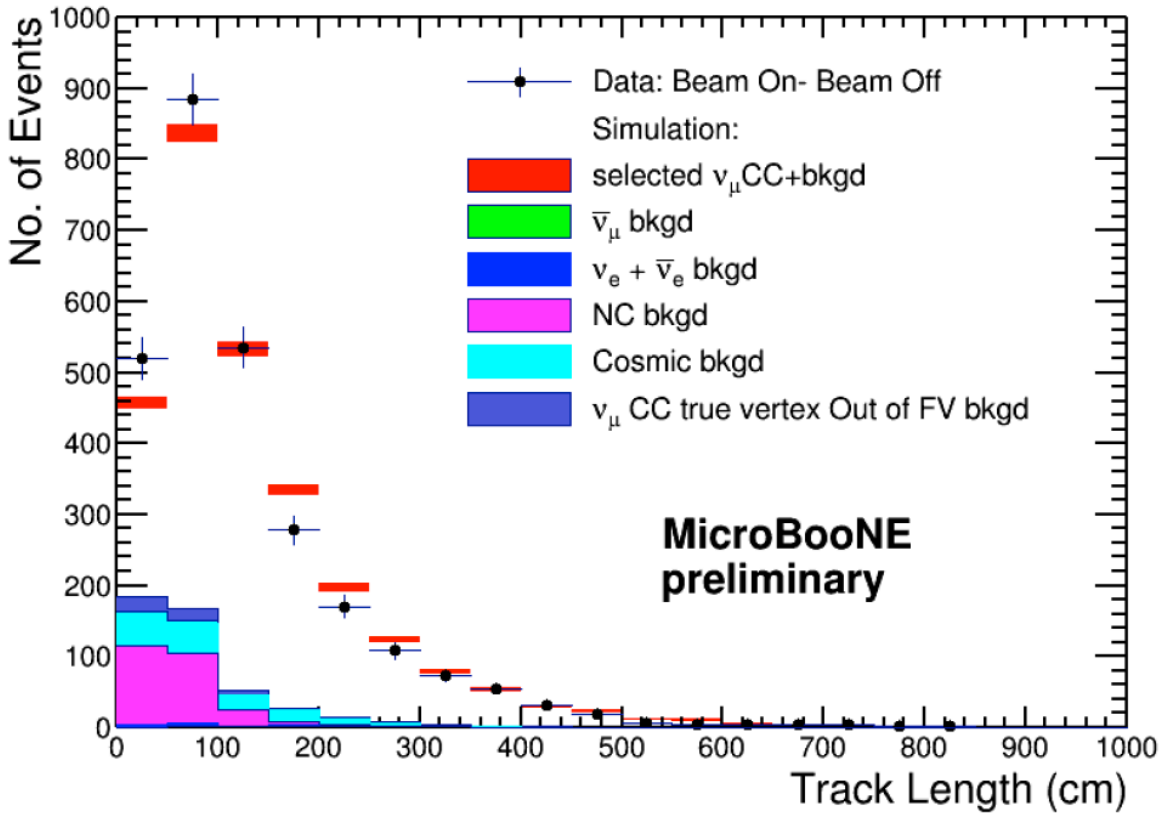
Performance



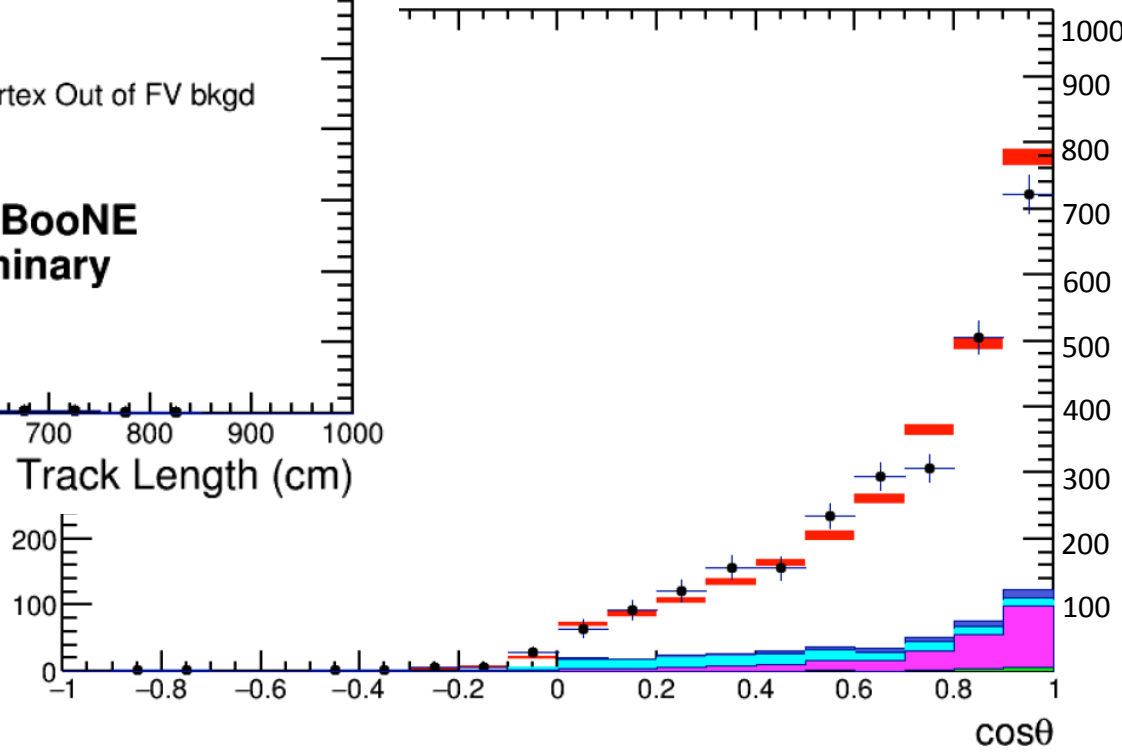


- Global efficiencies and purities:
  - Selection 1 – 12% efficiency, 55% purity
  - Selection 2 – 30% efficiency, 65% purity
- Efficiencies **include acceptances** – only 1/3 of events are contained
- Selections pick up **different topologies**, so only ~30% overlap

Event distributions



Selection II shown – Selection I in backups
Statistical errors only (both data and MC)

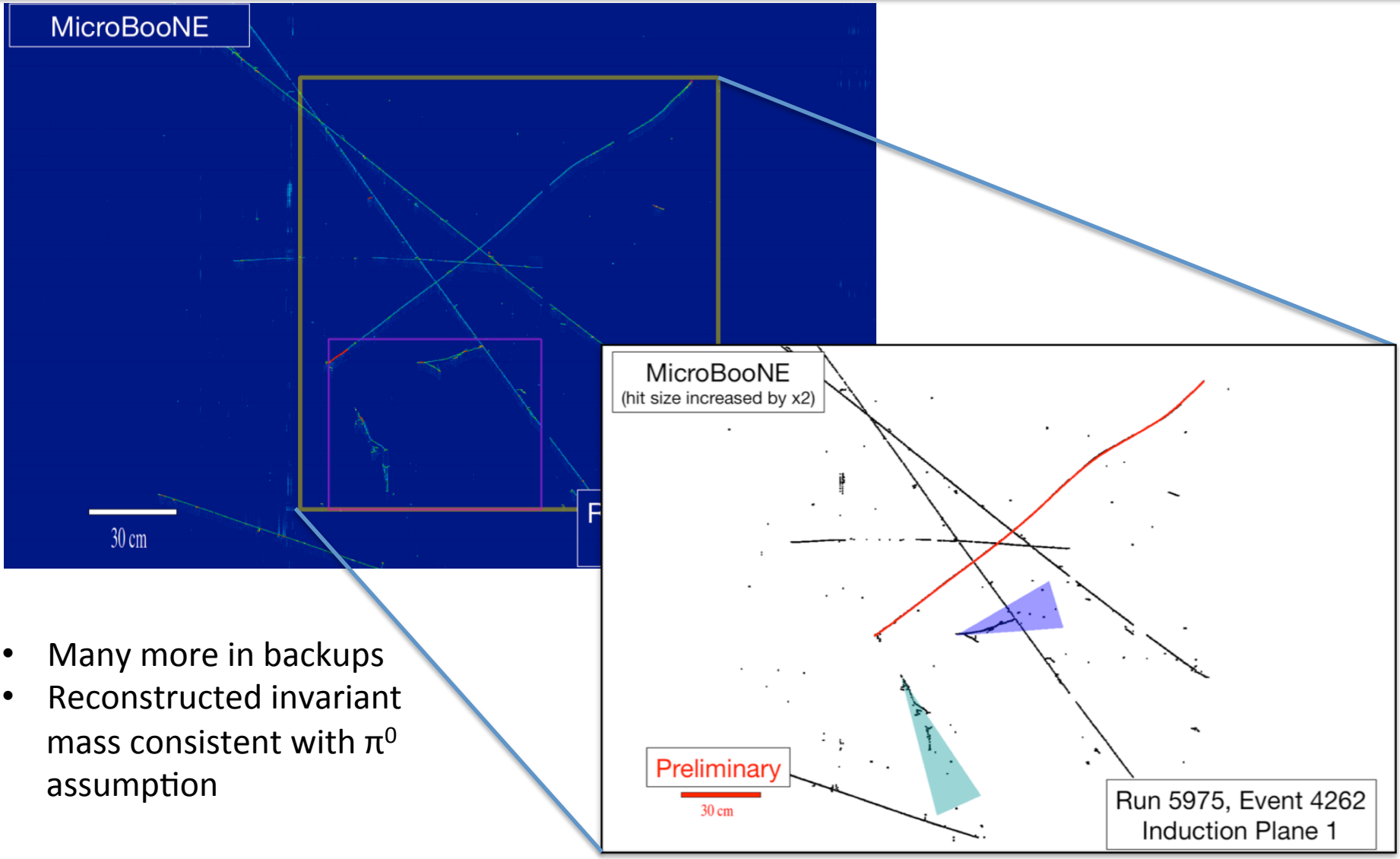


- **Shape-normalised event rate**
- **Track length includes contained and uncontained**

CCπ^0 selection

- Critical on the path to a **low-energy excess search**
- First steps in:
  - Shower reconstruction
  - Calorimetry
  - Estimation of NCπ^0 background
- **Multiple paths taken**
  - 2D-only reconstruction
  - Full **3D reconstruction**
  - Image processing and **pattern recognition**

Pi0 event displays



- Many more in backups
- Reconstructed invariant mass consistent with π^0 assumption

MicroBooNE public notes

- All the results described here, and more, are available on the MicroBooNE public notes page
- This page provides much more detailed information
- Find it here:
  - http://www-microboone.fnal.gov/publications/publicnotes/index.html

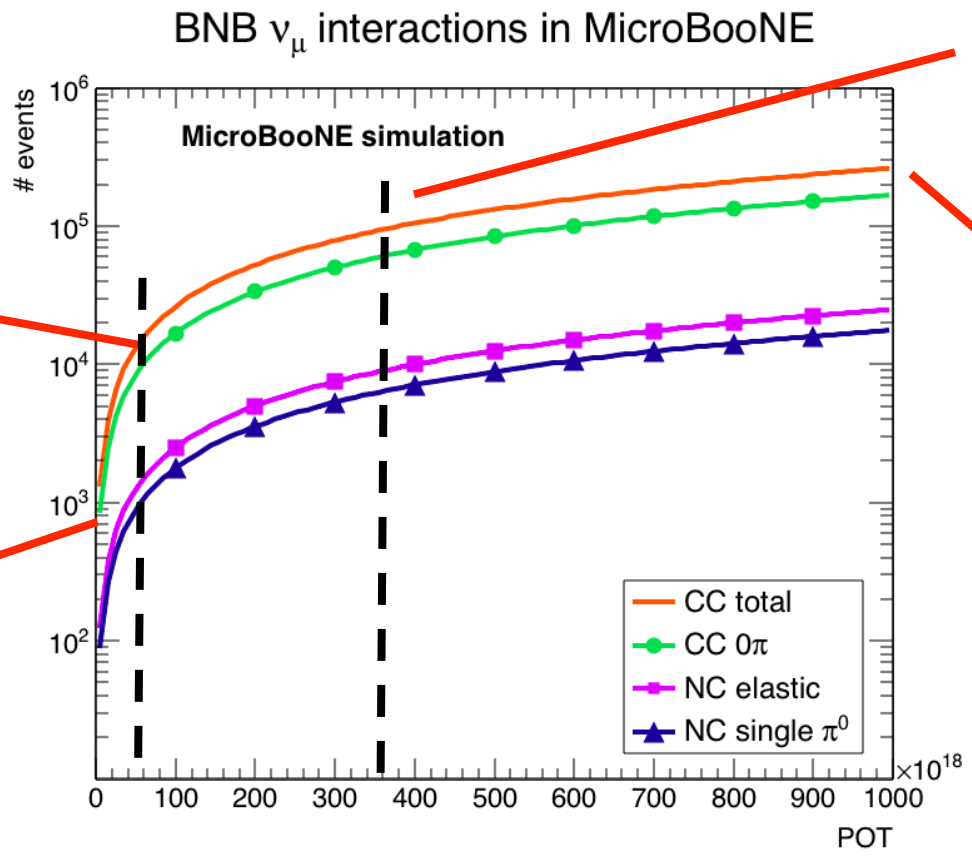
Future work

Summer upgrades

- Cosmic Ray Tagger system
  - Can't bury MicroBooNE, but we can tag entering cosmic muons
- Hardware noise filtering
  - Additional HV supply filter
  - Modified front end electronics boards
- Improved beam timing system

These, and more, are being implemented between August and October

Event rates



Total collected POT to date

Current unblinded data set

Approved POT with SBN

ArgoNEUT statistics

Future cross section programme

- **ν_μ CC-inclusive**
  - Differential cross section soon
- **ν_μ CC-exclusive** measurements
  - CC-0π
  - CC-Nπ
  - Track multiplicity
  - Proton kinematics
  - Kaon production
- **ν_μ NC** measurements
  - NC-elastic
  - NC-π^0
- Many more!
  - ν_e CC-inclusive
  - NuMI measurements!

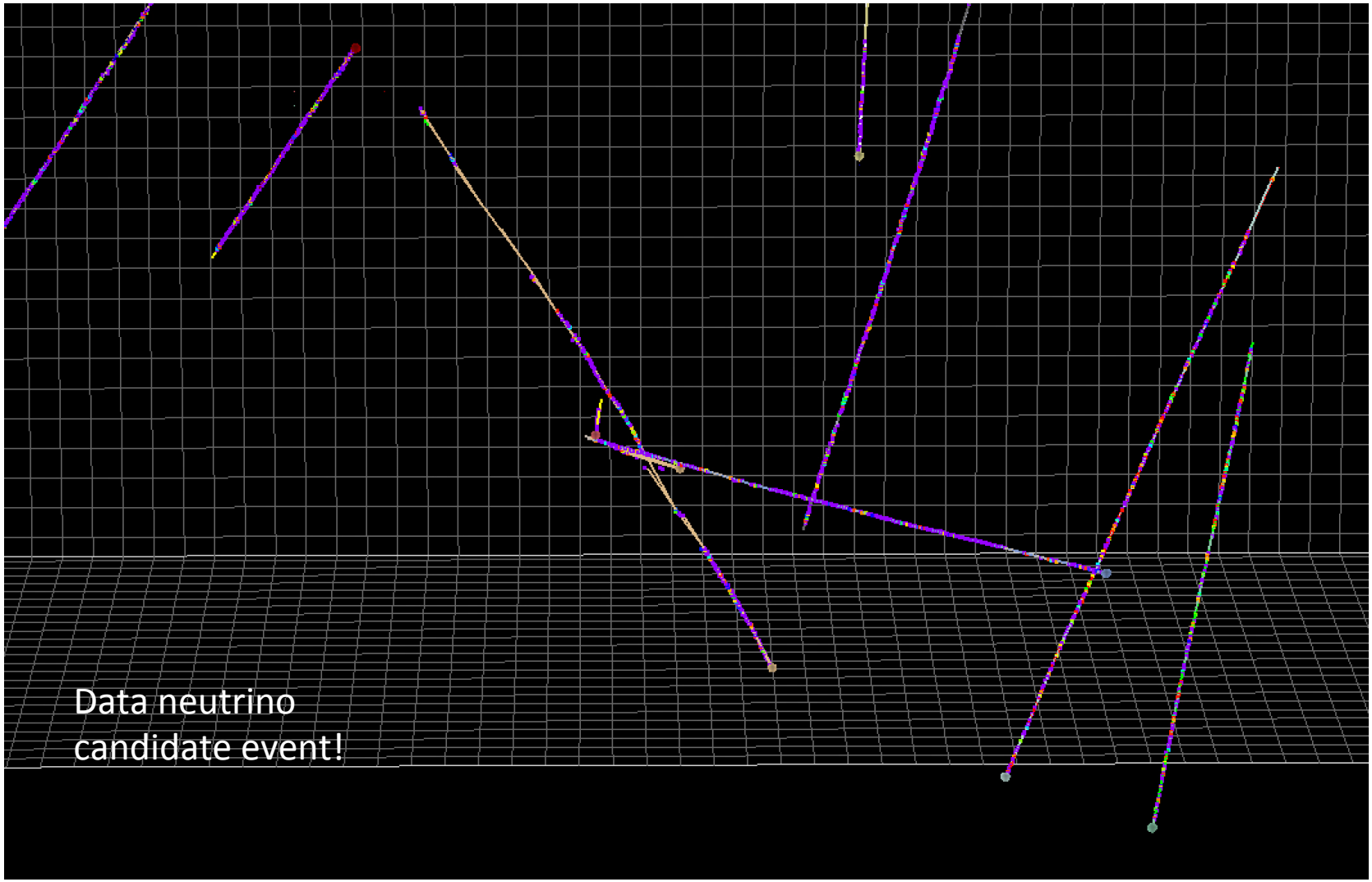
analyses underway!

critical for oscillation analysis

Conclusions

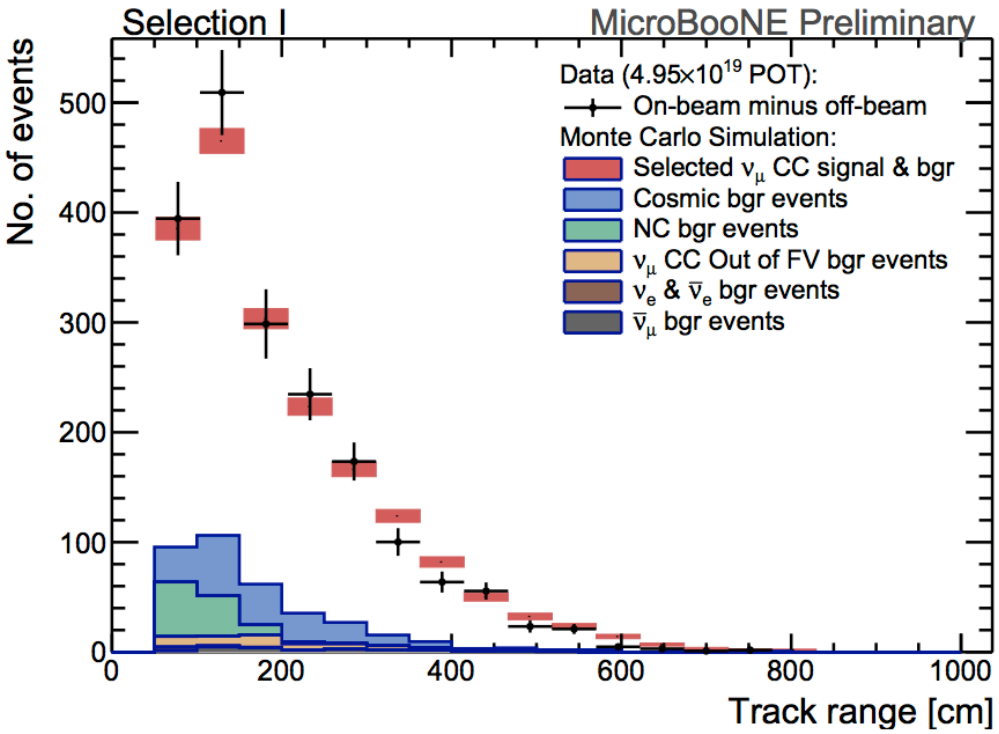
- MicroBooNE is now running and our detector is performing very well
  - Now making good progress analysing run 1 data
- Many **detector physics** and **cross section** results to come
- **CC-inclusive** sample produced
  - Will be used to constrain (flux) x (xsec) in an oscillation analysis
- **Michel electron** and **neutral pion** samples identified
  - Demonstrates **shower reconstruction, calorimetry**
- All of this is progress towards a **low-energy excess** search
  - Requires further tool development and **more data**

Thank you

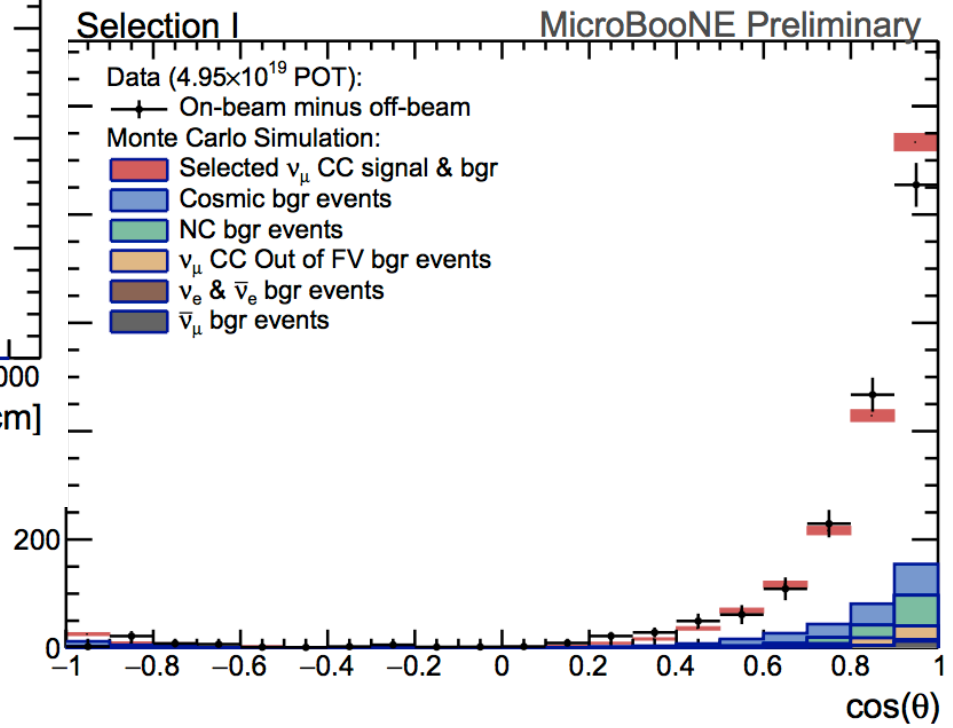


Backup slides

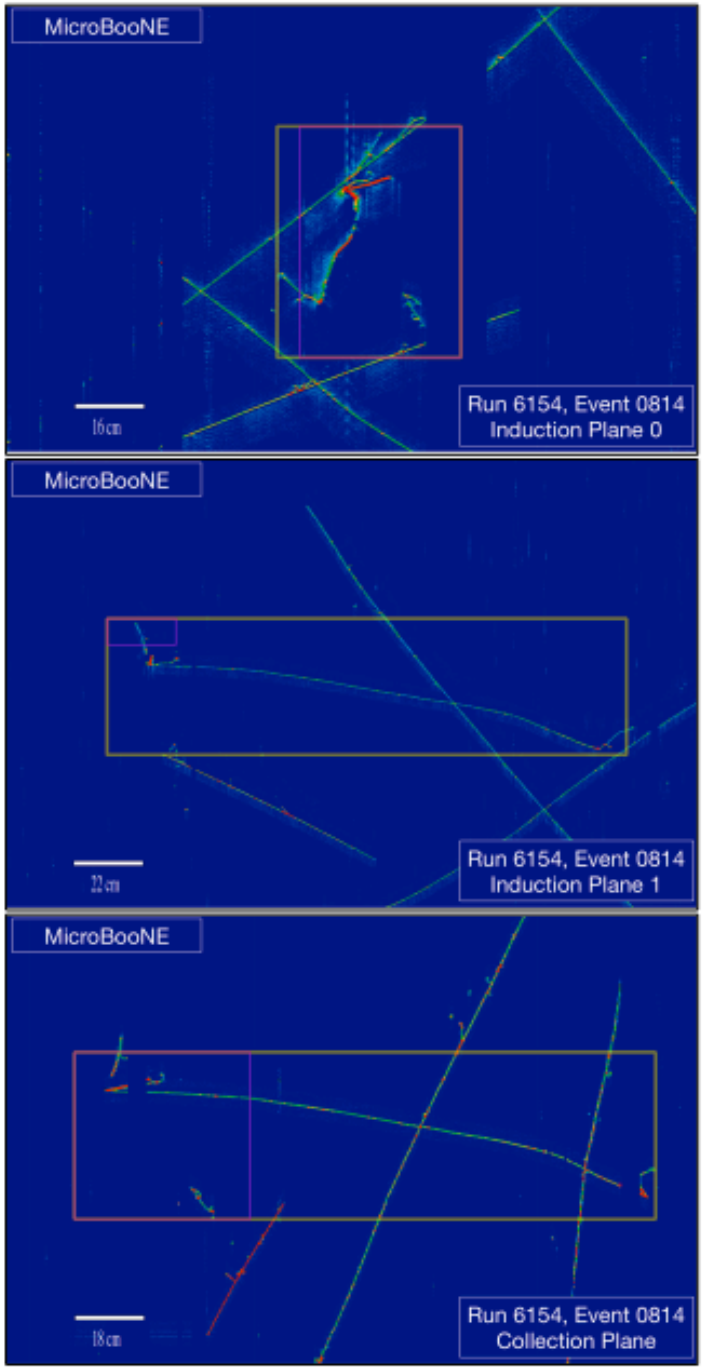
Selection I distributions



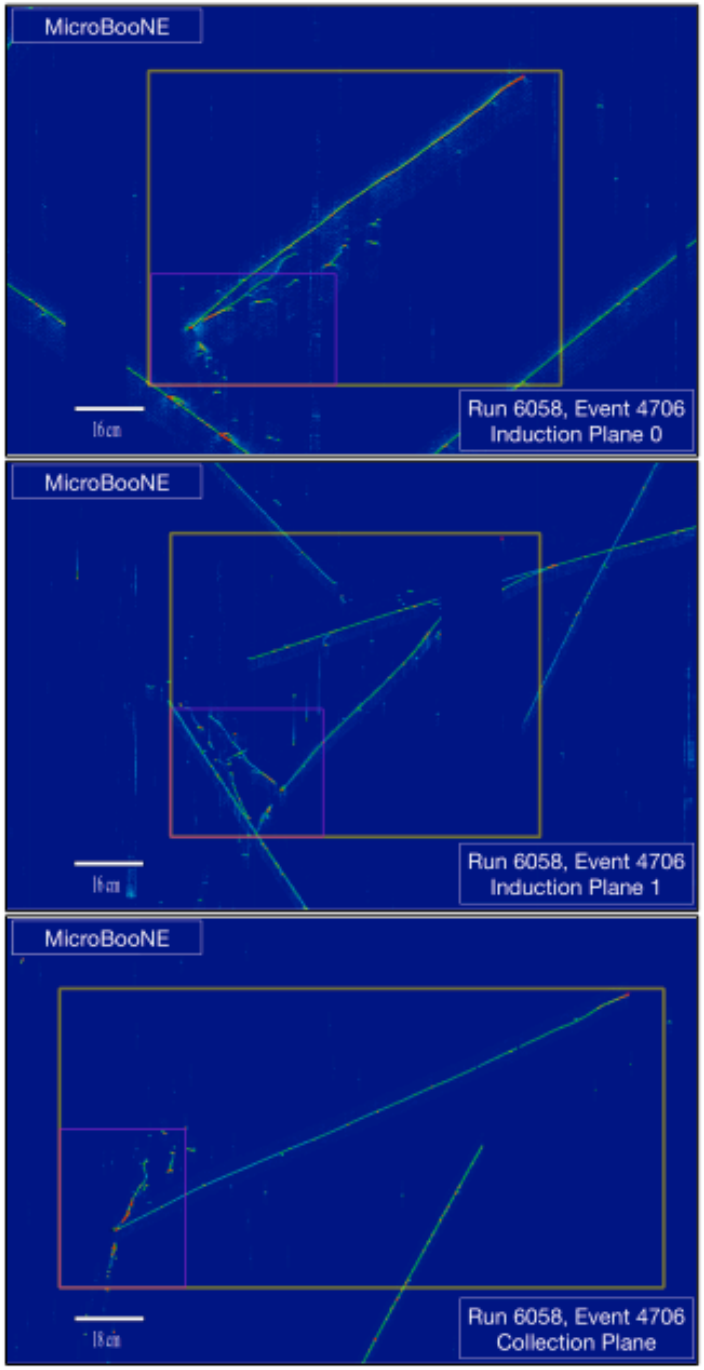
(a) Selection I



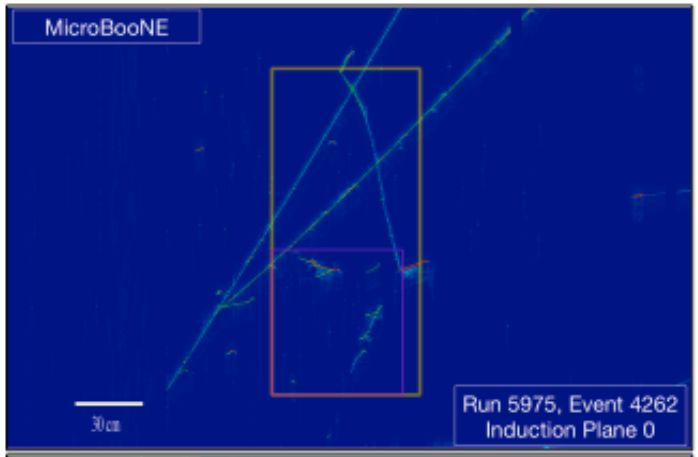
(a) Selection I



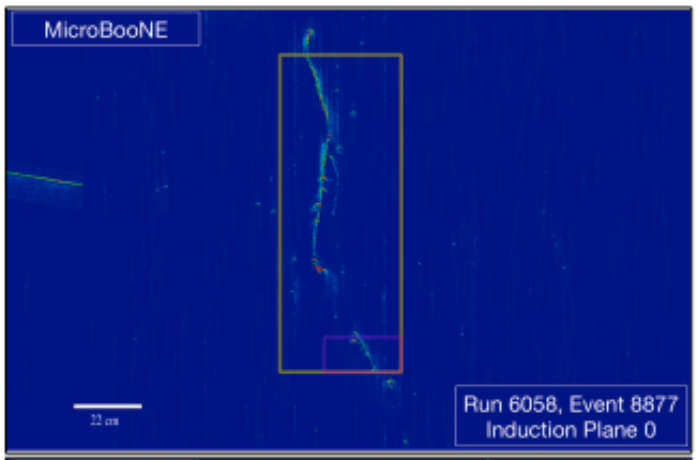
(a) (Run 6145, Subrun 16, Event 814)

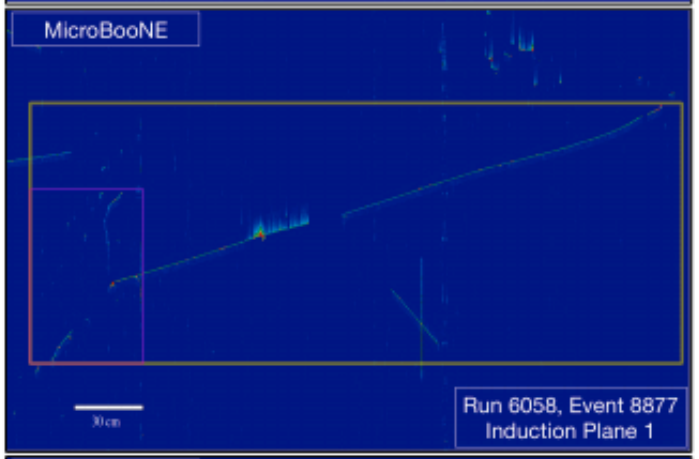


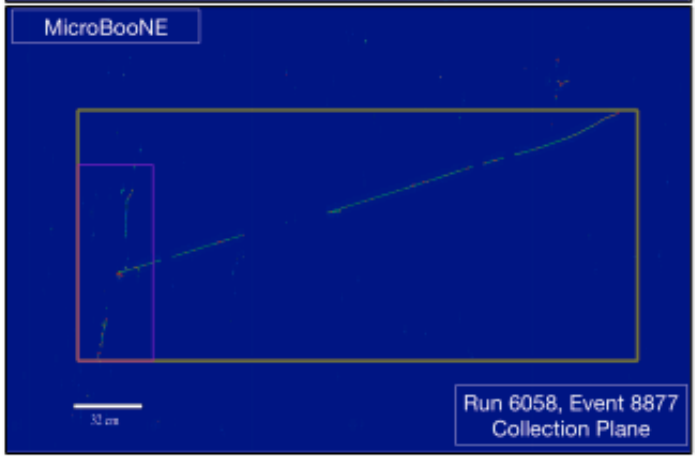
(b) (Run 6058, Subrun 94, Event 4706)



(c) (Run 5975, Subrun 85, Event 4262)

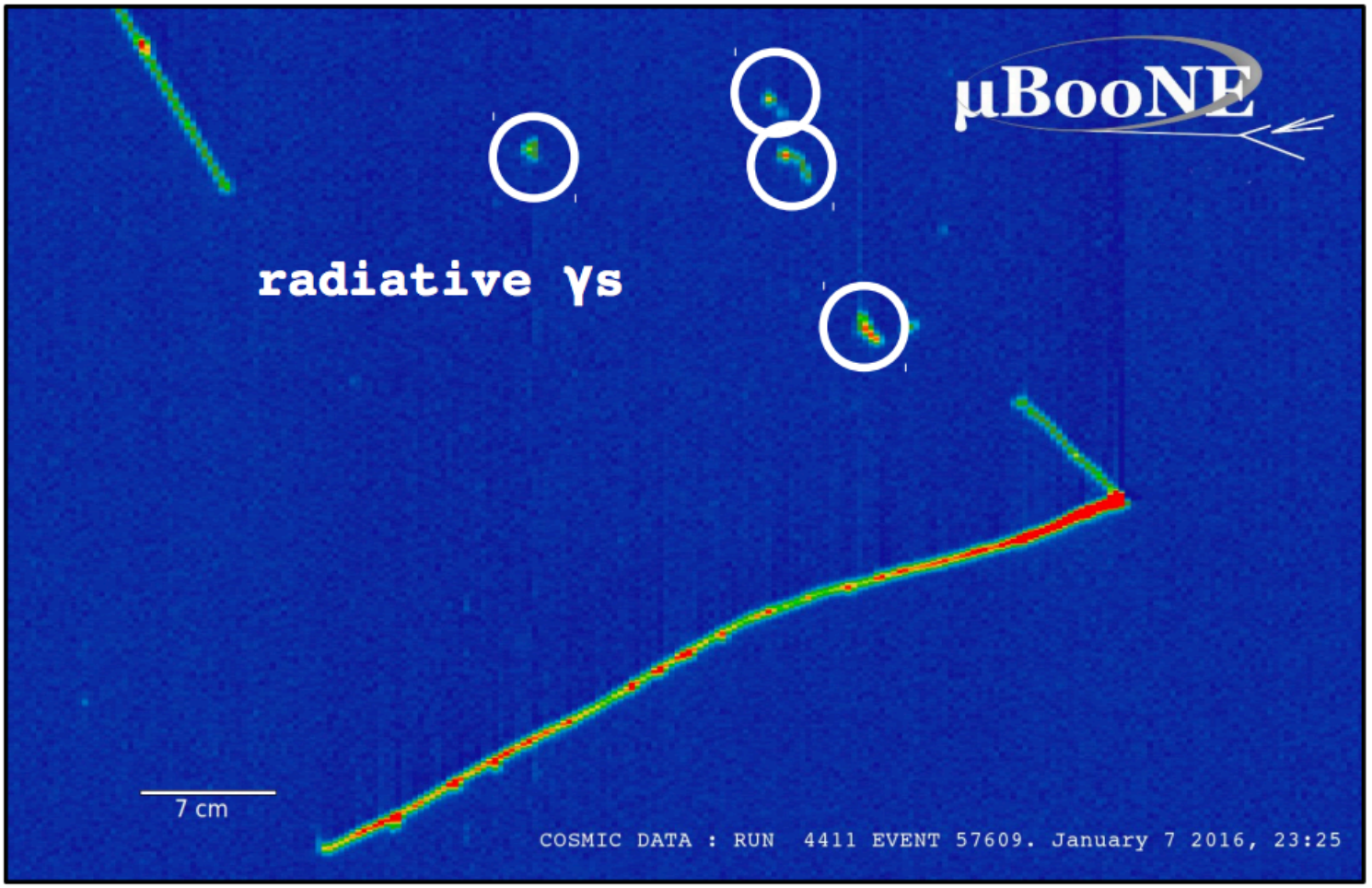






(d) (Run 6058, Subrun 177, Event 8877)

Radiative photon losses



Noise level (ENC)

- Noise post-filtering rises linearly with wire length