Reconstructing ν_μ with Deep Learning in MicroBooNE

CEA — DPhP — 12/11/2018

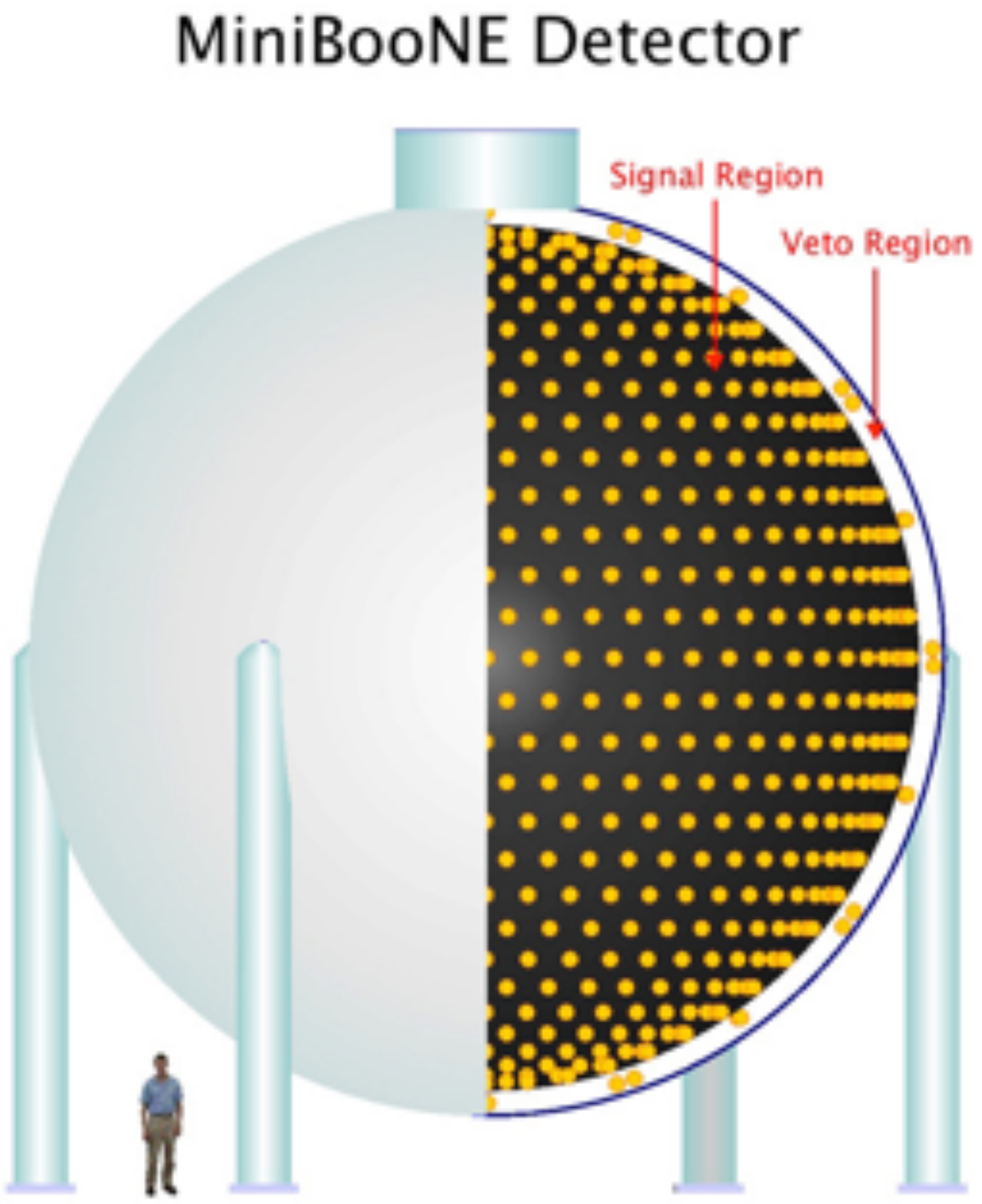
Adrien Hourlier
Massachusetts Institute of Technology
on behalf of the
MicroBooNE collaboration

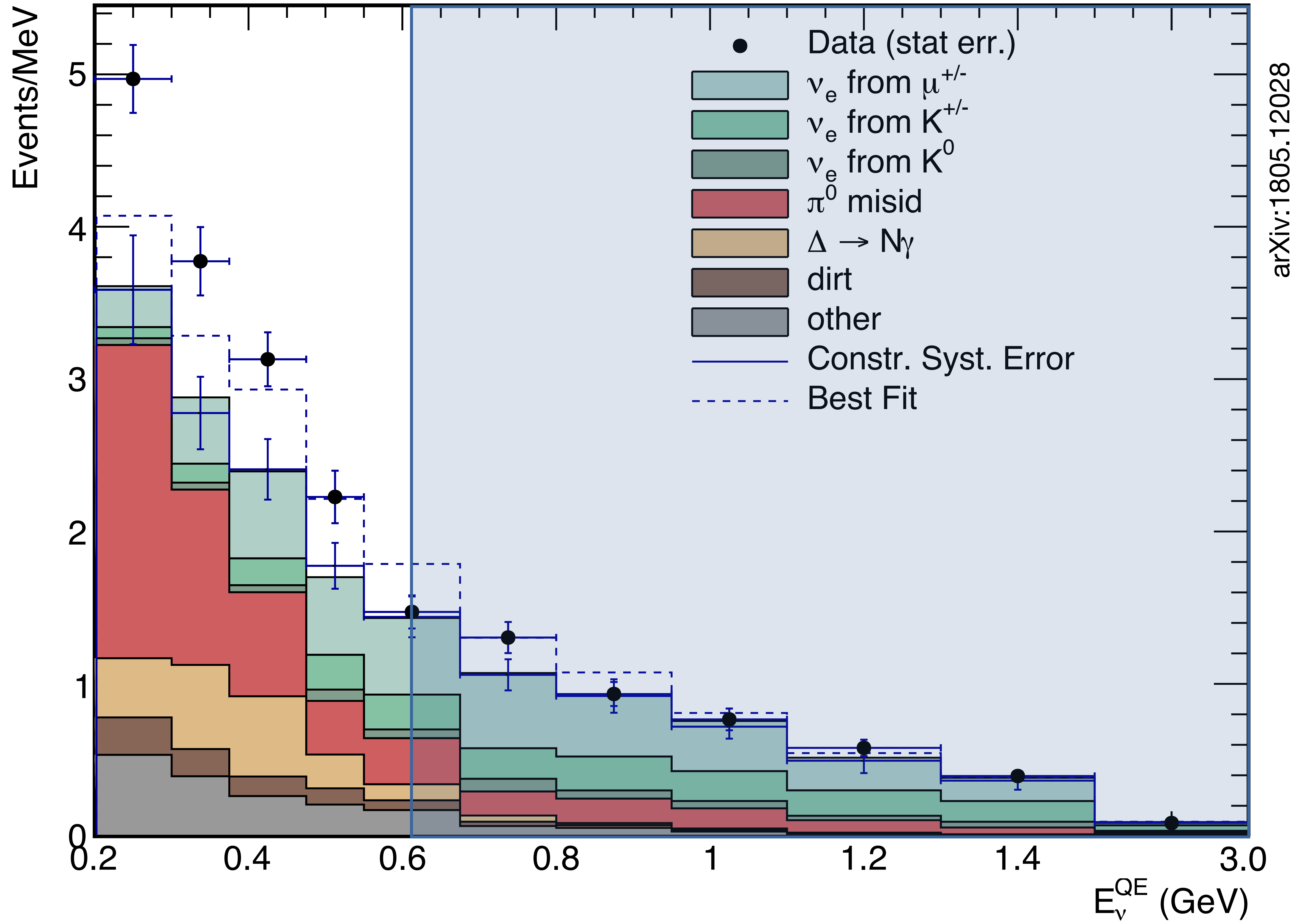
Overview

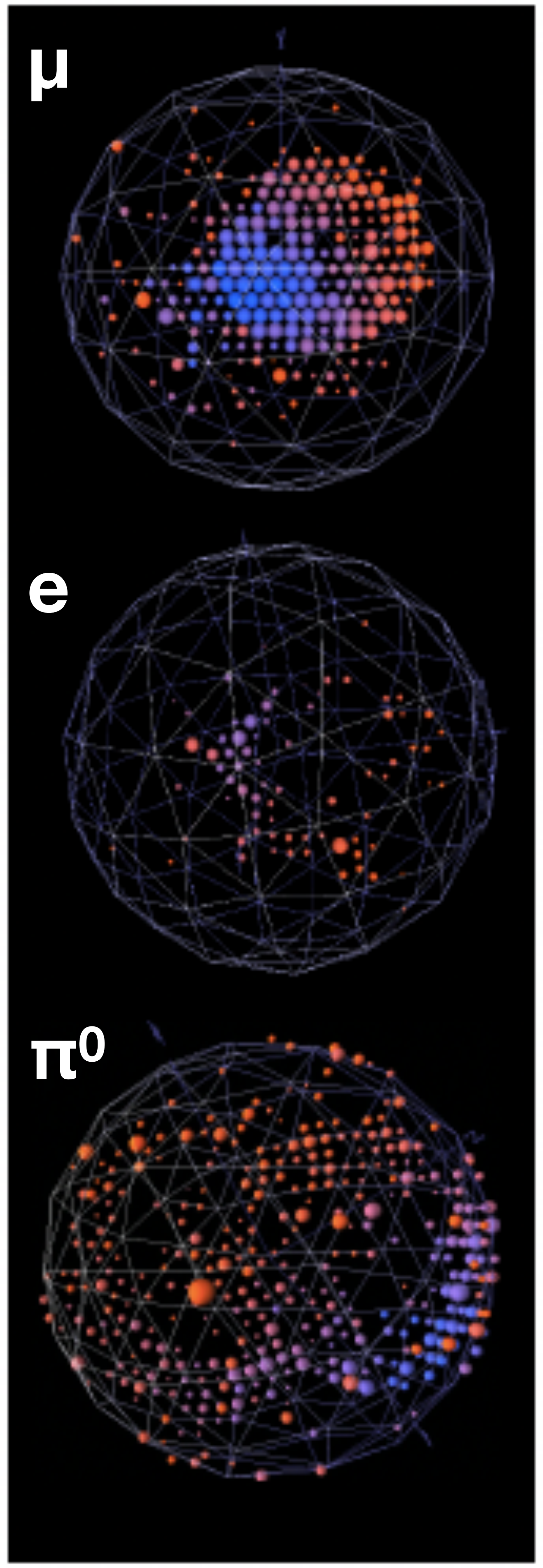
- **Low Energy ν_e appearance Excess**
- **MicroBooNE experiment**
- **MicroBooNE LEE searches**
- **The Deep Learning LEE search**

Low Energy Excess

- LSND and MiniBoonE observed an excess of ν_e appearance at low energies
- Best fit in tension with global 3+1 neutrino models



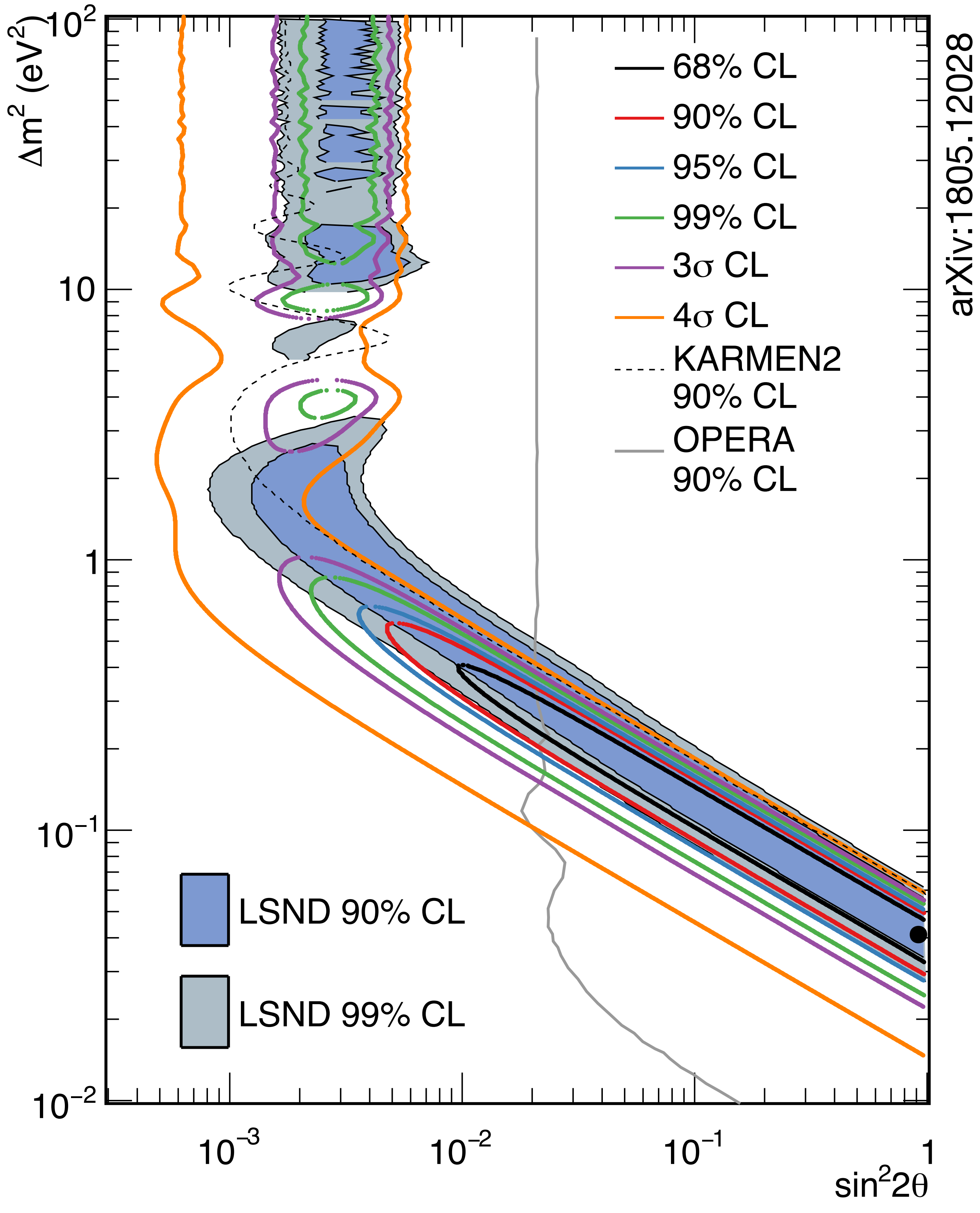




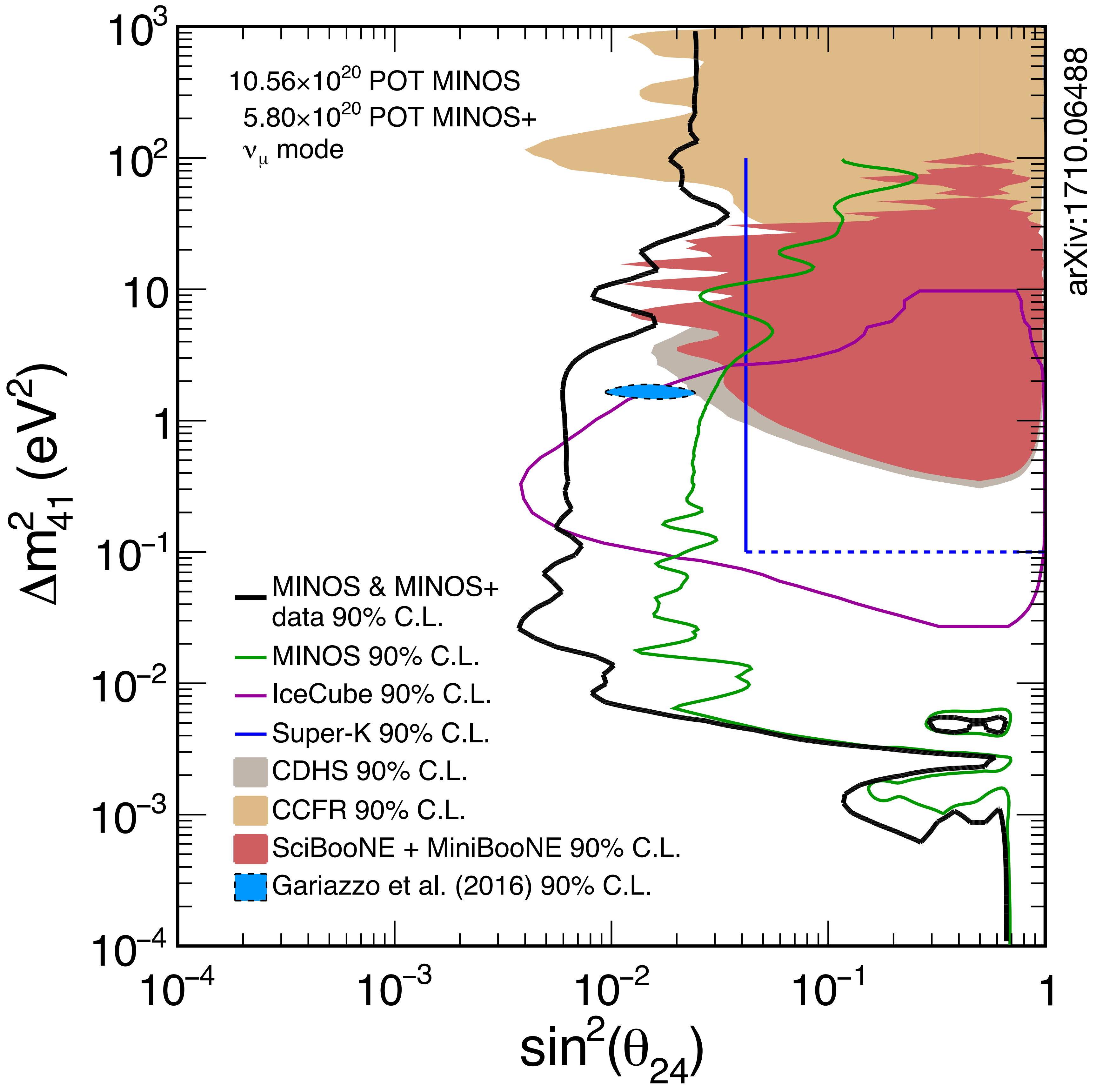
Low Energy Excess

- ν_e **appearance :**
  - KARMEN ⟶ **limit**
  - ICARUS ⟶ **limit**
  - NOMAD ⟶ **limit**
  - OPERA ⟶ **limit**
  - MiniBooNE ⟶ **signal**
  - LSND ⟶ **signal**
- ν_e **disappearance :**
  - KARMEN + LSND ⟶ **limit**
  - Reactor Anomaly ⟶ **signal**
  - Neutrino-4 ⟶ **signal** (arxiv 1809.10561)
  - ILL ⟶ **signal** (arxiv 1802.07763)
- ν_μ **disappearance :**
  - MiniBoonE + SciBooNE ⟶ **limit**
  - MINOS ⟶ **limit**
  - CCFR, CDHS ⟶ **limit**
  - IceCube ⟶ **limit**

(here we call signal a 2σ effect)



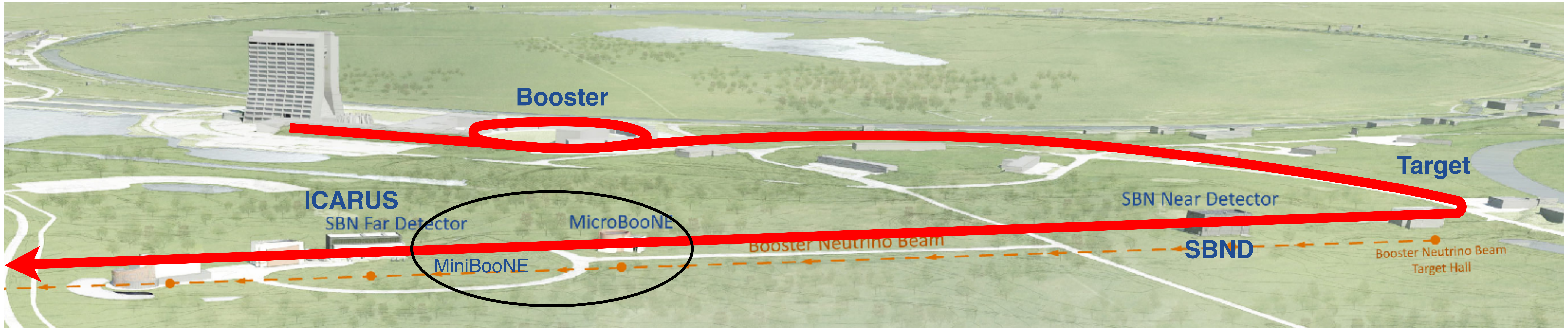
Appearance



Disappearance

Fermilab Neutrino Beamlines

The Booster Neutrino Beamline

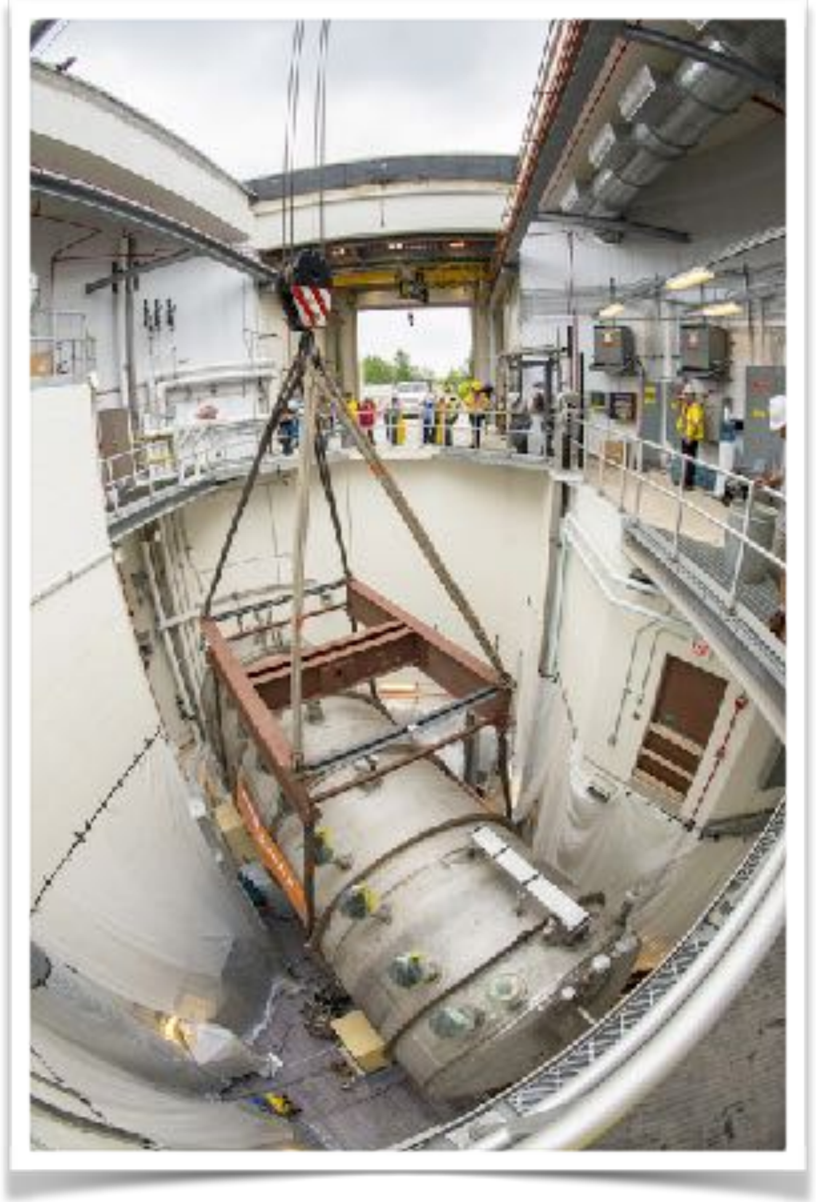


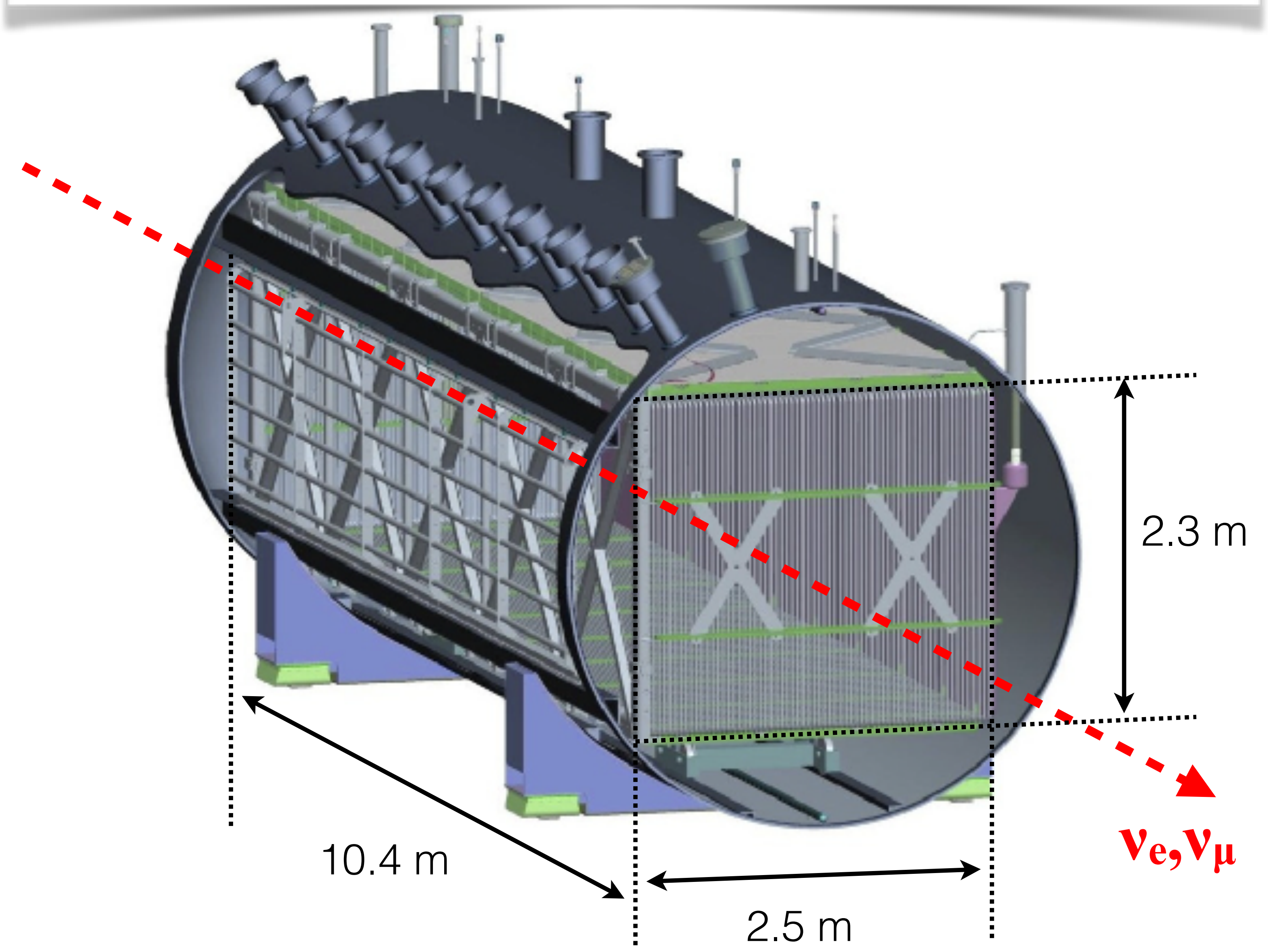
- 8 GeV protons from the Booster, beam spill at 5Hz
- Hosts the Short Baseline Neutrino Program :
  - SBN Near Detector
  - MicroBooNE
  - ICARUS
- 3 detectors, same target nucleus, same operational technology
- Definitive test of LSND oscillation using three baselines
- Simultaneous ν_μ disappearance and ν_e appearance searches

The MicroBooNE Experiment

- MicroBooNE is a neutrino experiment using a **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber (LArTPC)
- **Physics Goals of MicroBooNE :**
  - To investigate the MiniBooNE and LSND ν_e appearance excess at low energy – to confirm or deny potential evidence for sterile neutrinos
  - To measure neutrino-argon cross section around 1 GeV
  - To pursue R&D studies for LArTPC operations and exploitation for larger programs (SBN, protoDUNE, DUNE)

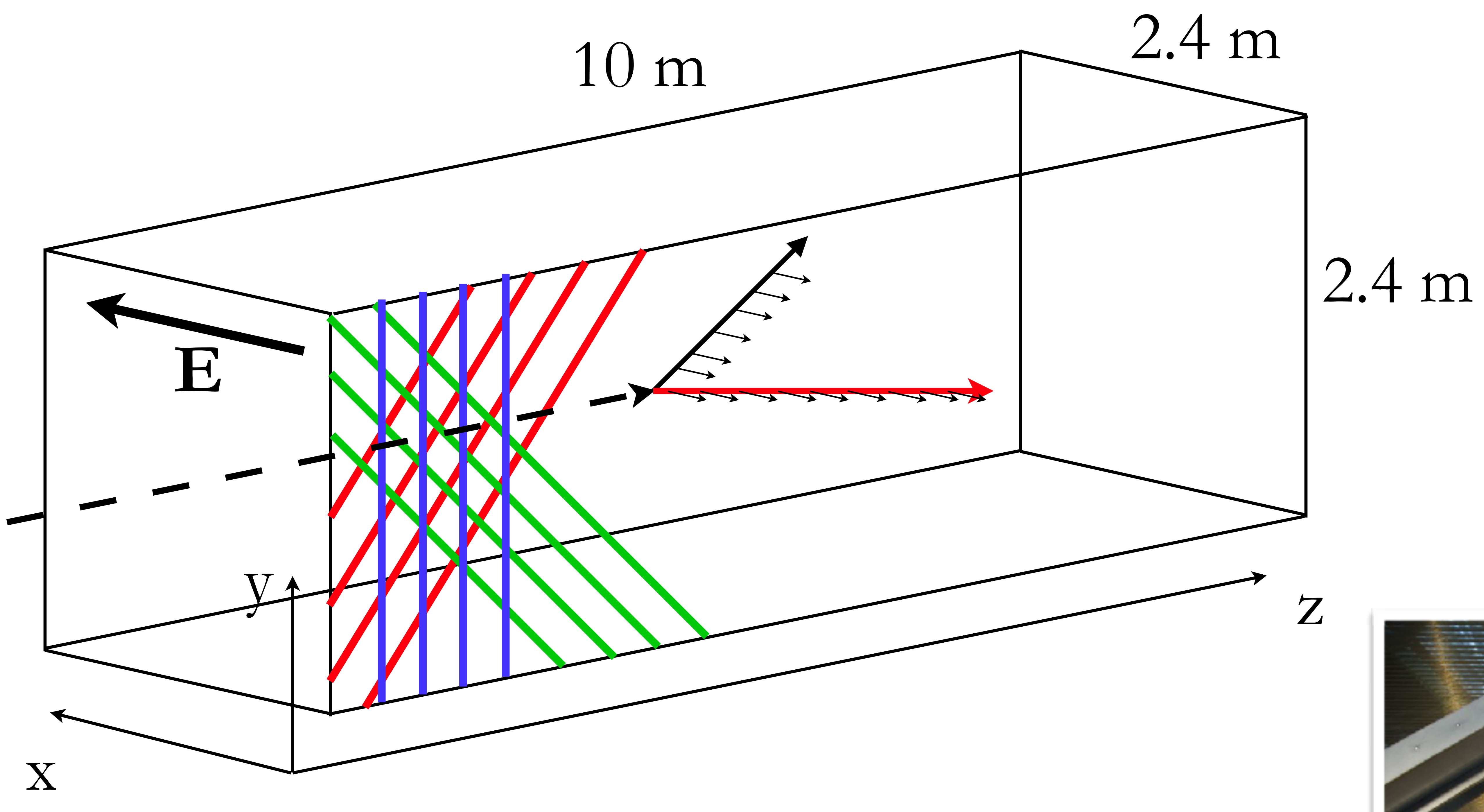
The MicroBooNE Detector



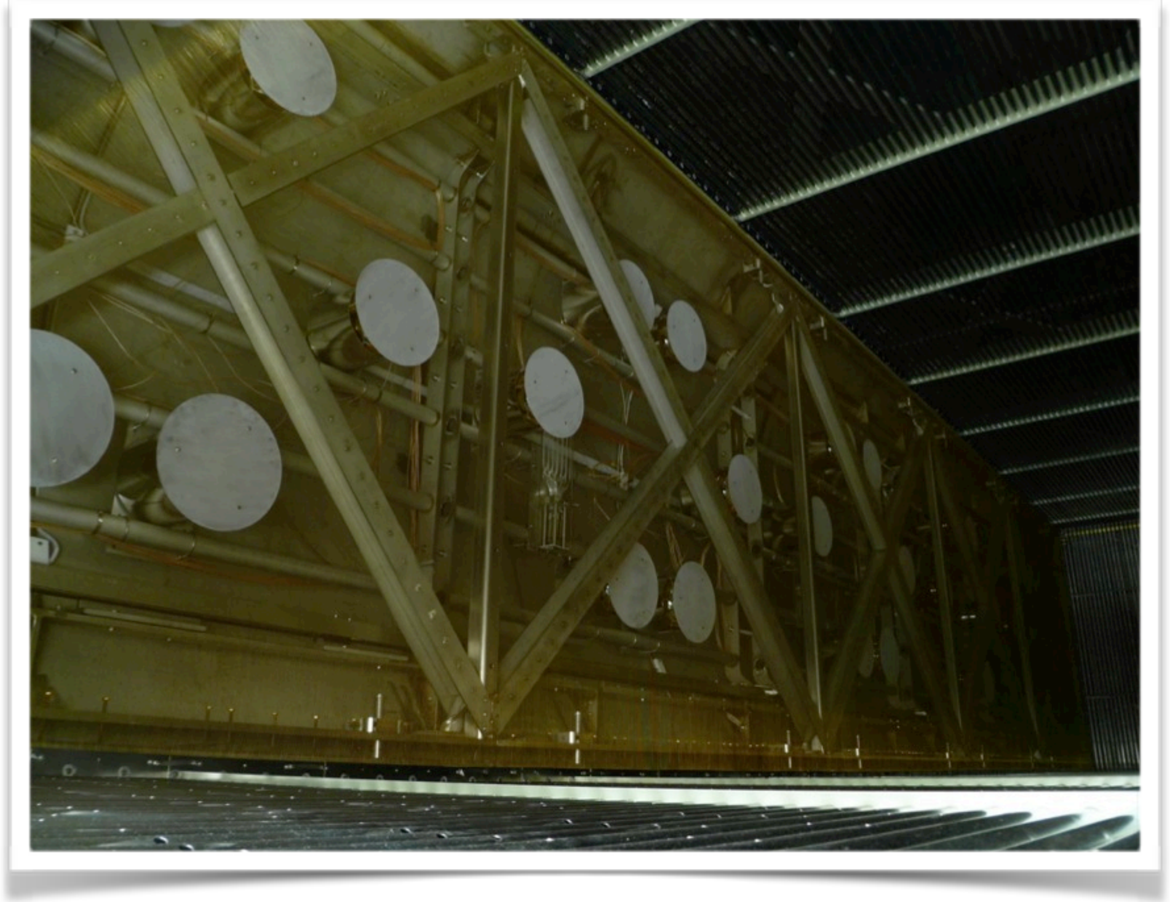


- **Micro Boo**ster **N**eutrino **E**xperiment
- 85 ton active mass Liquid Argon TPC
- $\nu_\mu \longrightarrow \nu_e$ appearance experiment
- Booster Neutrino Beam-line
- Taking data since October 2015
- Cosmic ray tagger added in 2016
- > 97% detector up time
- 1.1×10^{21} POT delivered

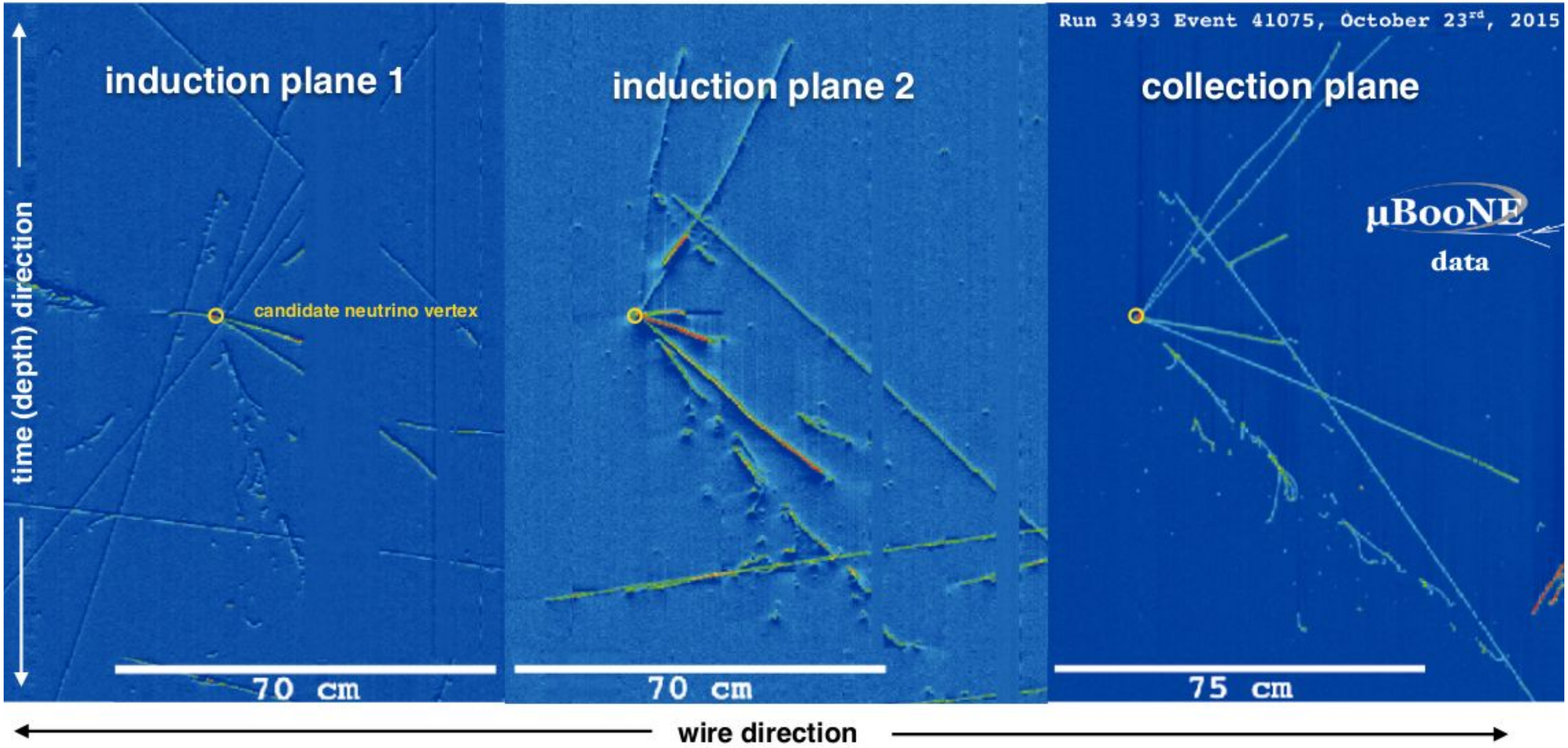
The MicroBooNE Detector



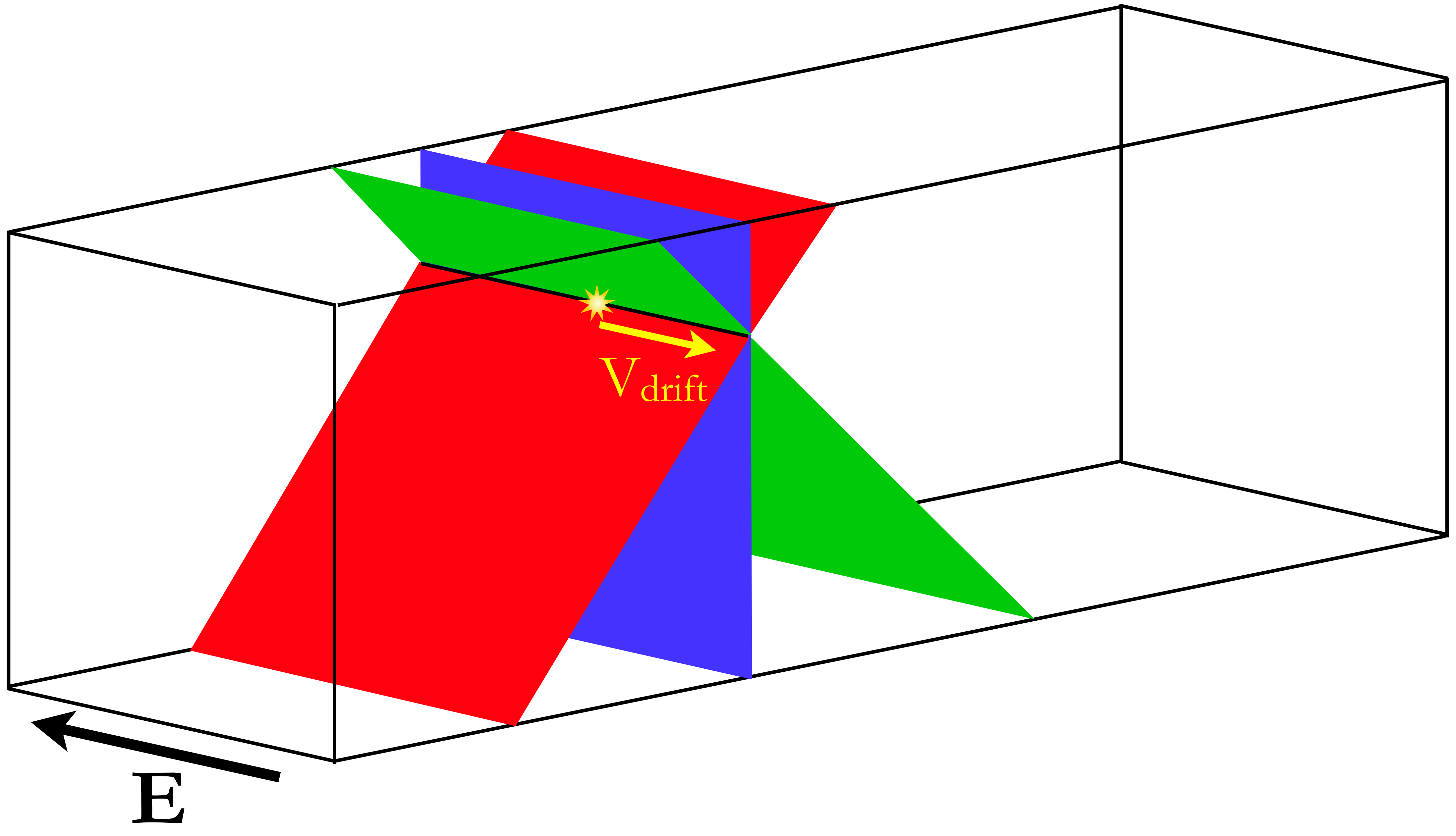
- Time Projection Chamber
- 85 active tons of Liquid Argon
- 32 cryogenic PMTs
- 2400 U-wires (+60°)
- 2400 V-wires (-60°)
- 3456 Y-wires (vertical)
- 3mm wire pitch



Raw Event Example

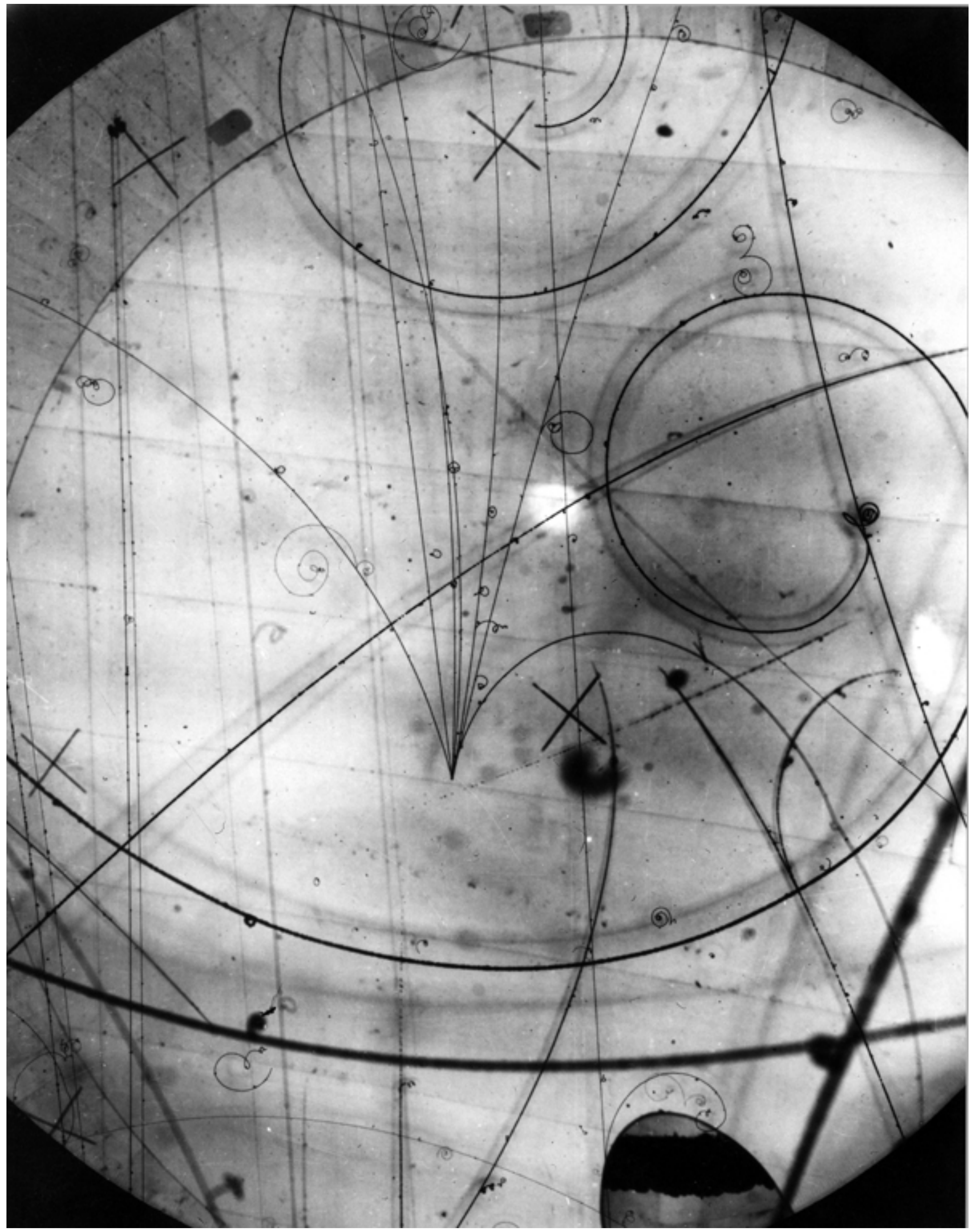


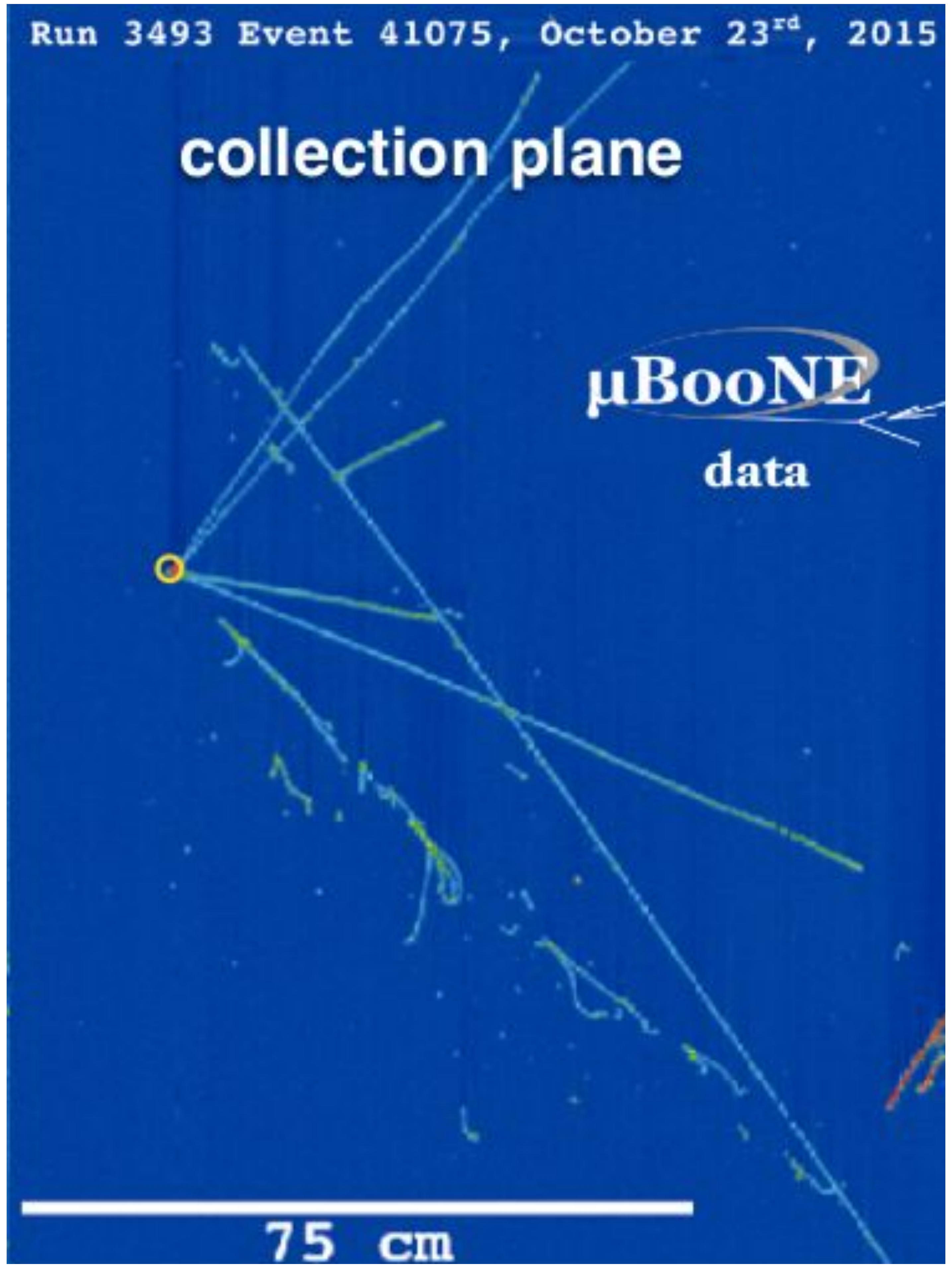
The MicroBooNE Detector



- A charge deposition in the detector drifts into a "unique" combination of U,V and Y wires
- There is actually a time degeneracy
- In the drift dimension, we need a T0, and the known drift speed to get the position
- T0 is given by
    - trigger time (we know when neutrinos interact)
    - PMT signal

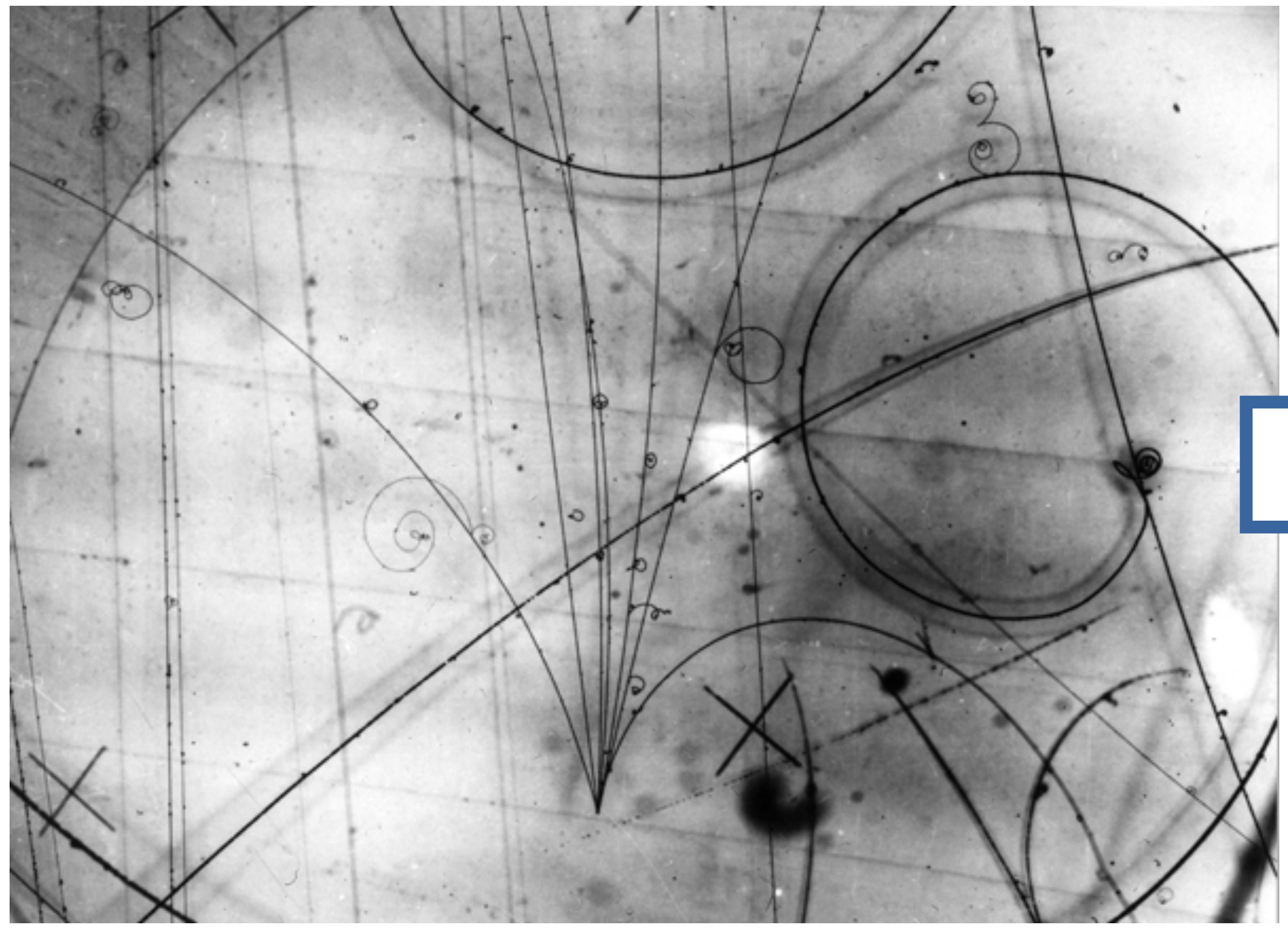
LArTPC : why are they so cool?

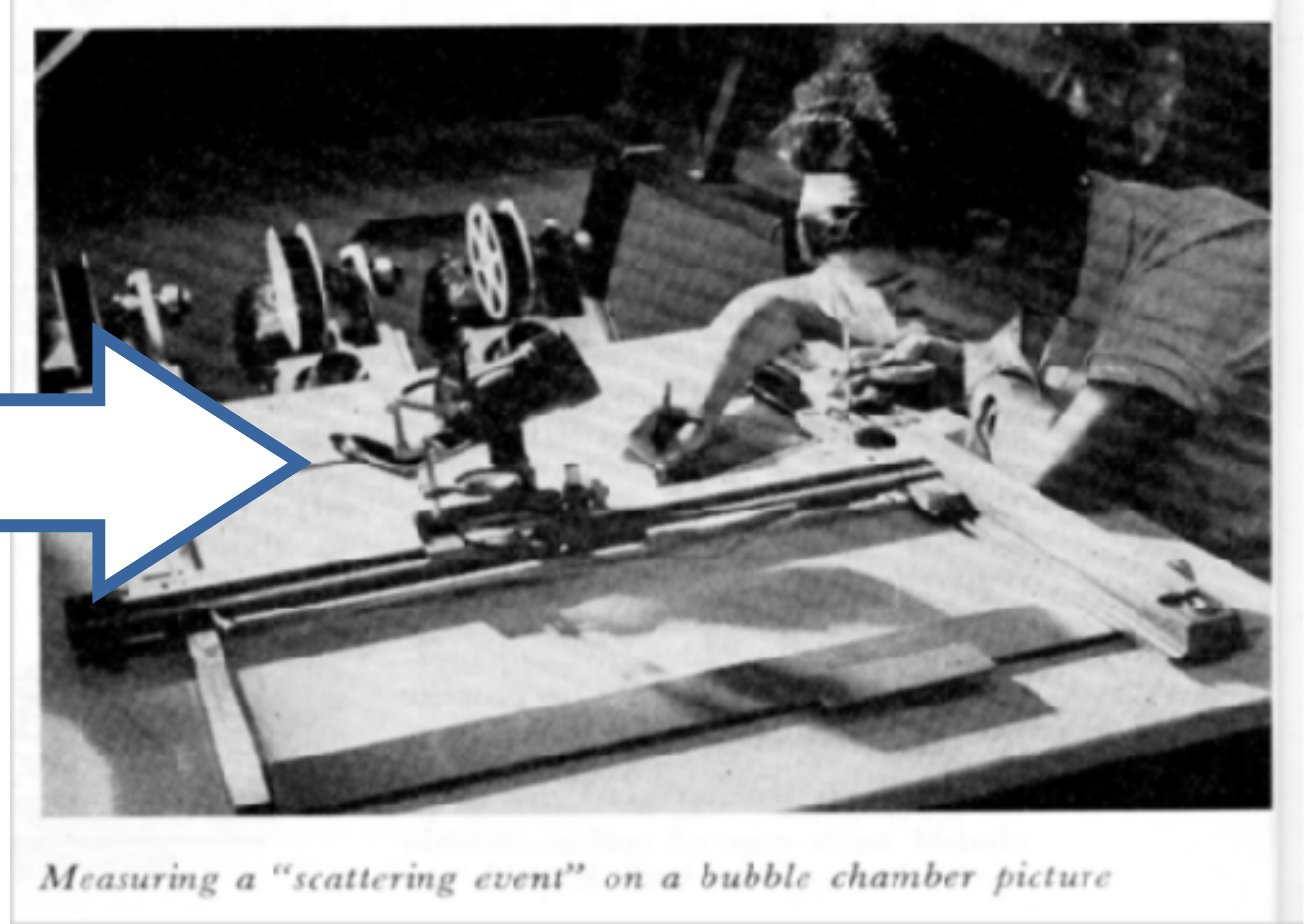


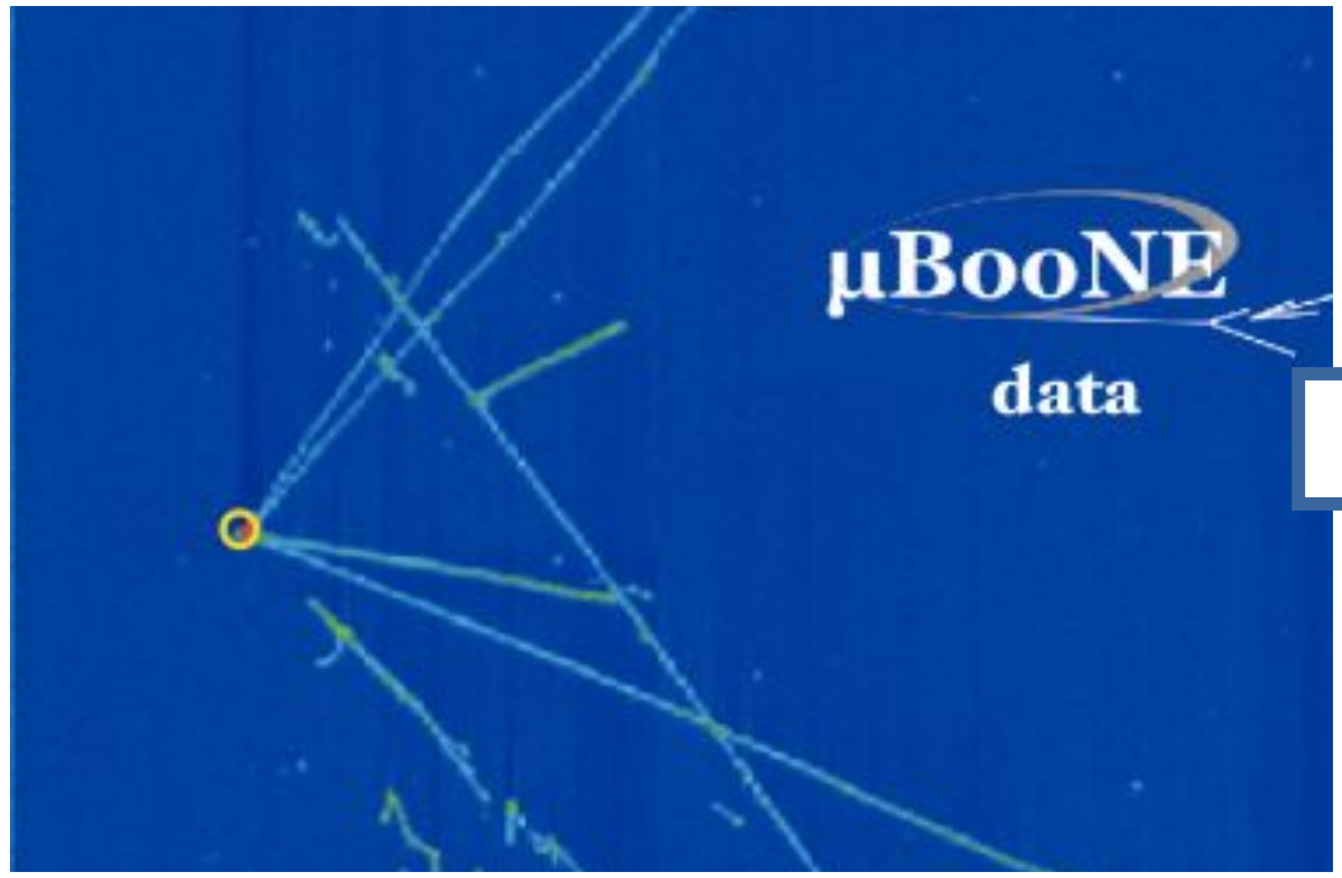


- LArTPCs produce bubble chamber-like images!
- Able to "see" the interaction
  - more "intuitive"
  - rely less on the light production model
  - can use event topology to reject background
- LArTPCs are ~1000x faster than bubble chambers
- LArTPCs produce digitized images, processed by computer

LArTPC : why are they so hard?







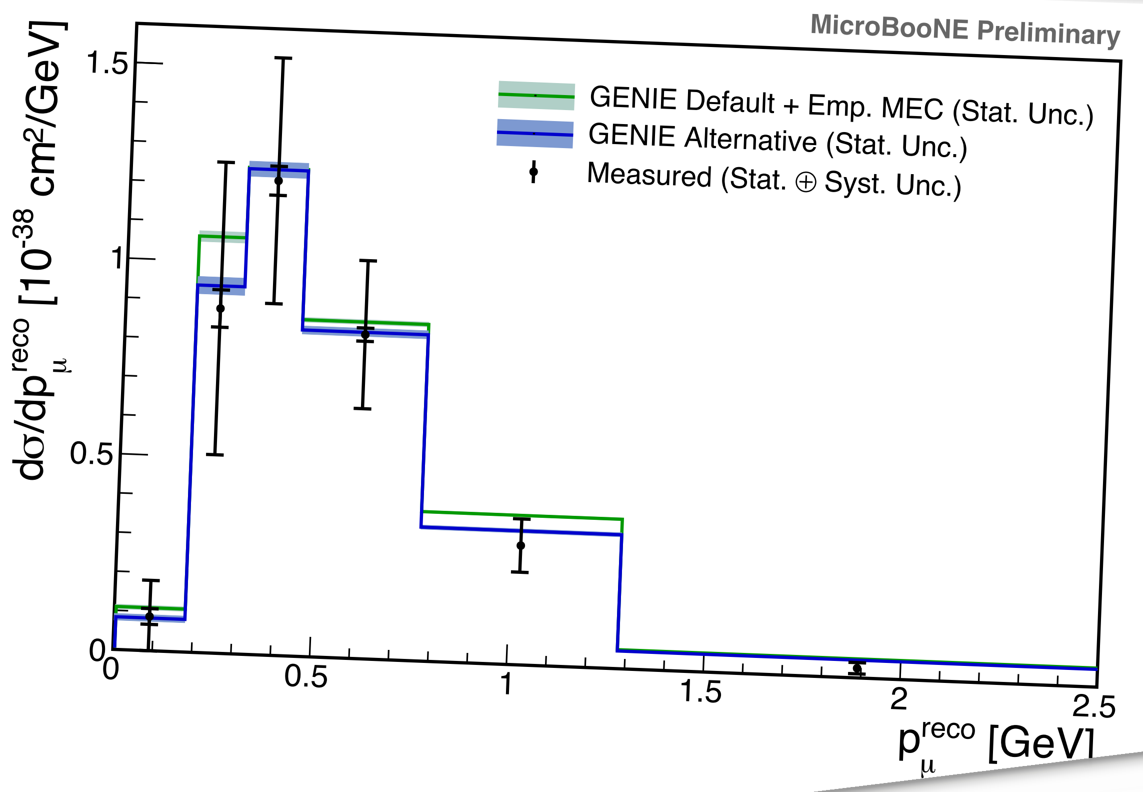
- Huge amount of data to process
- Pattern, topology (i.e. kinematics) is an important parameter, need algorithms smart enough to recognize them without bias and recognize backgrounds
- Some events are hard to identify, even for a trained human!

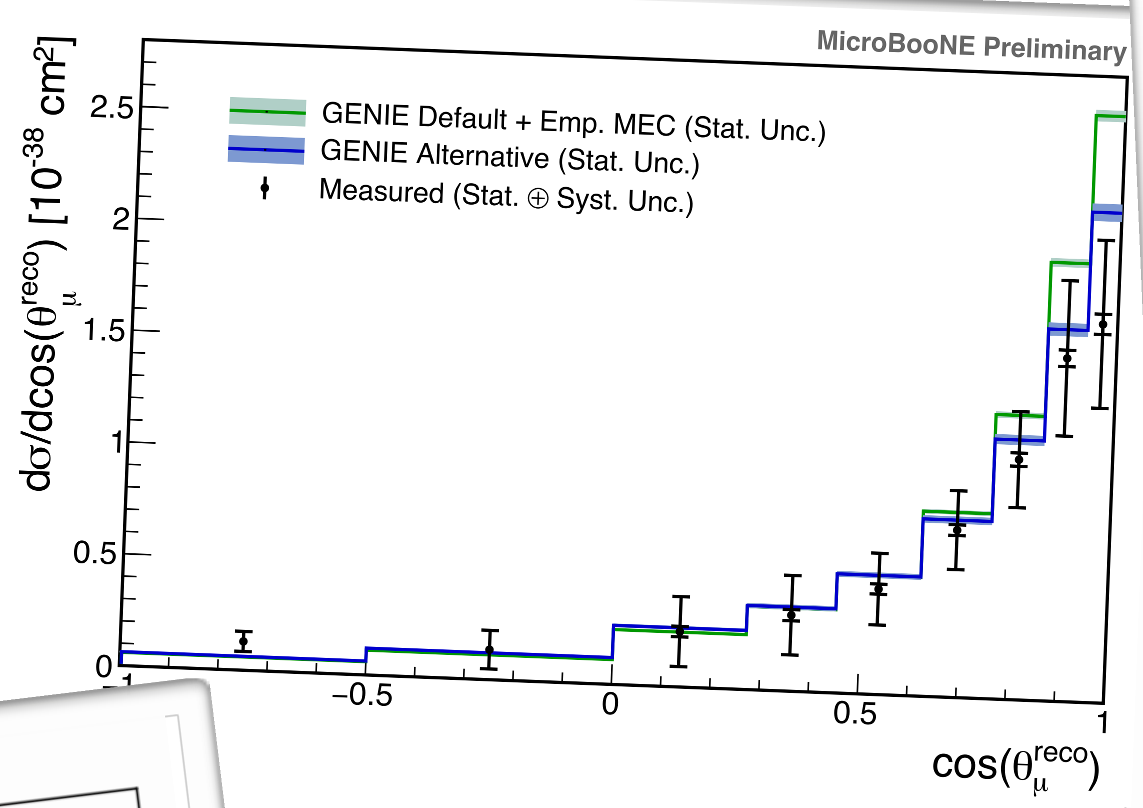
The Road to Low Energy Excess

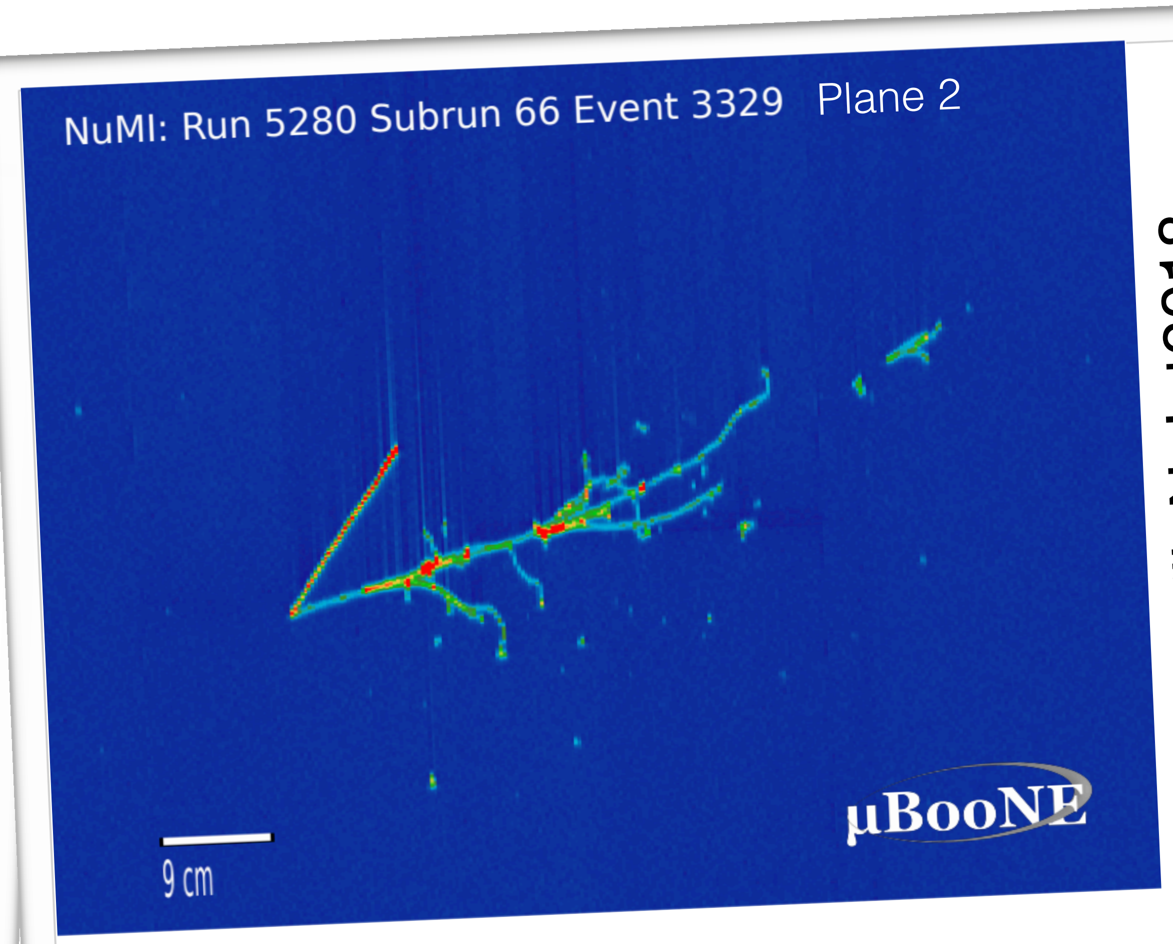
Recent Physics Results

CC Inclusive Cross Section
- High efficiency & purity
- Insensitive to hadrons
- Constrain ν_e rate

MICROBOONE-NOTE-1045-PUB

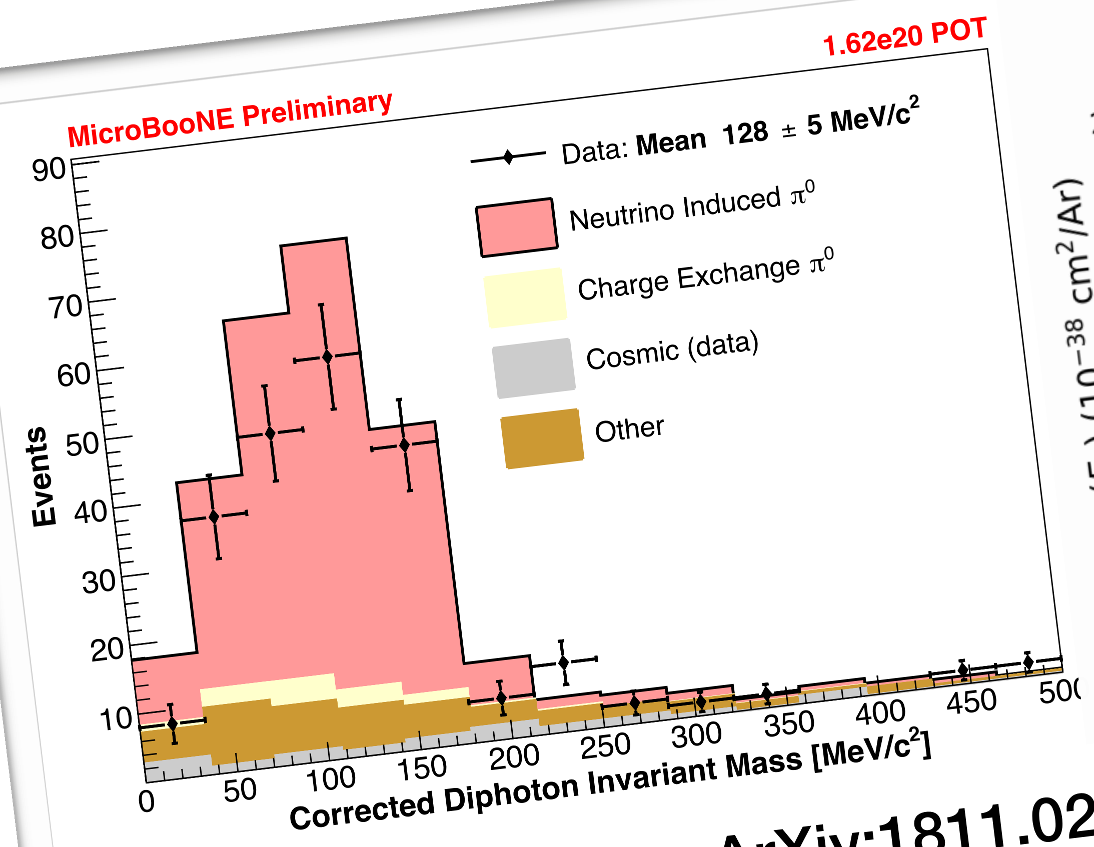


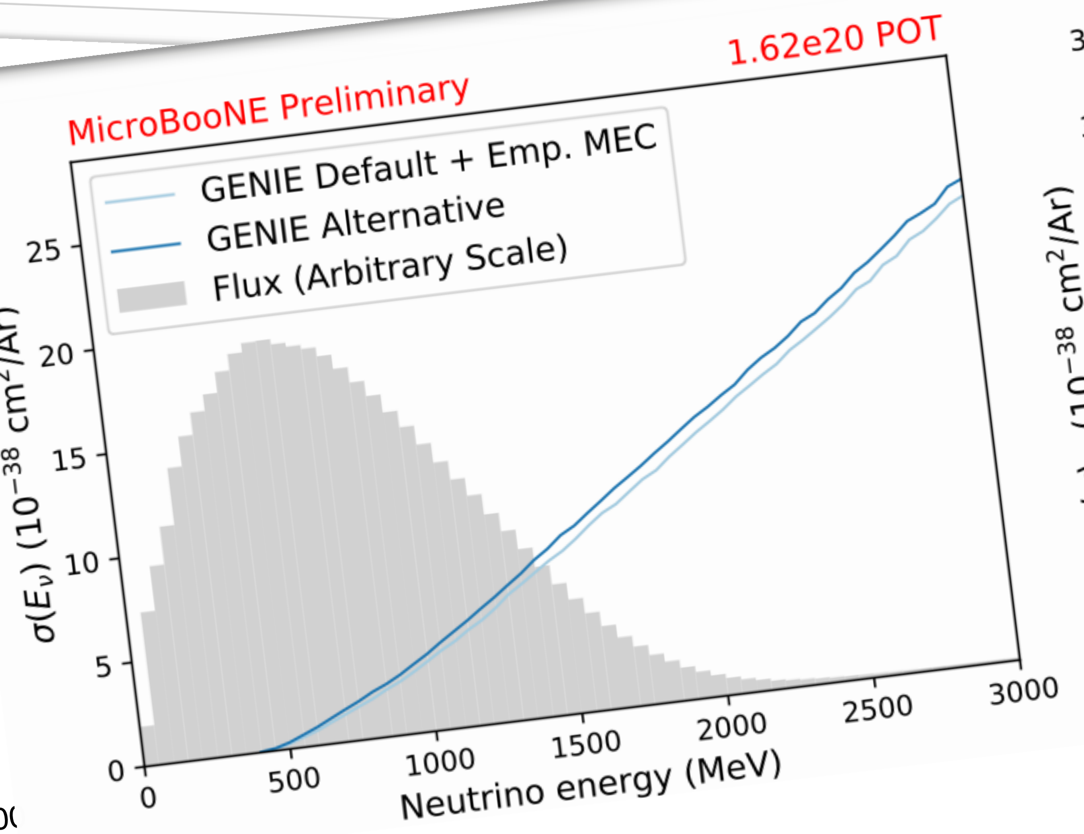


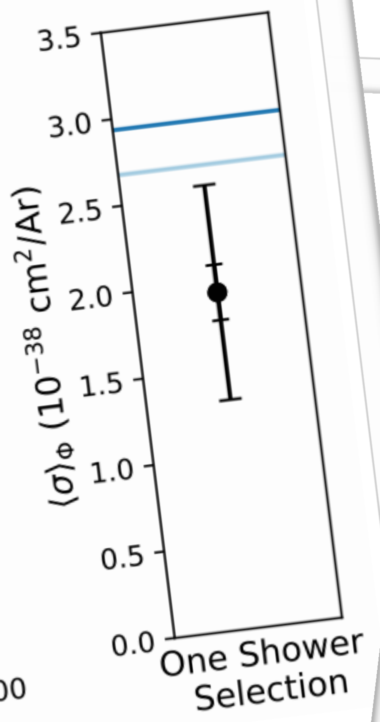


C. Hill, NuInt2018

NuMI ν_e Cross Section
- Larger ν_e event sample in off axis NuMI



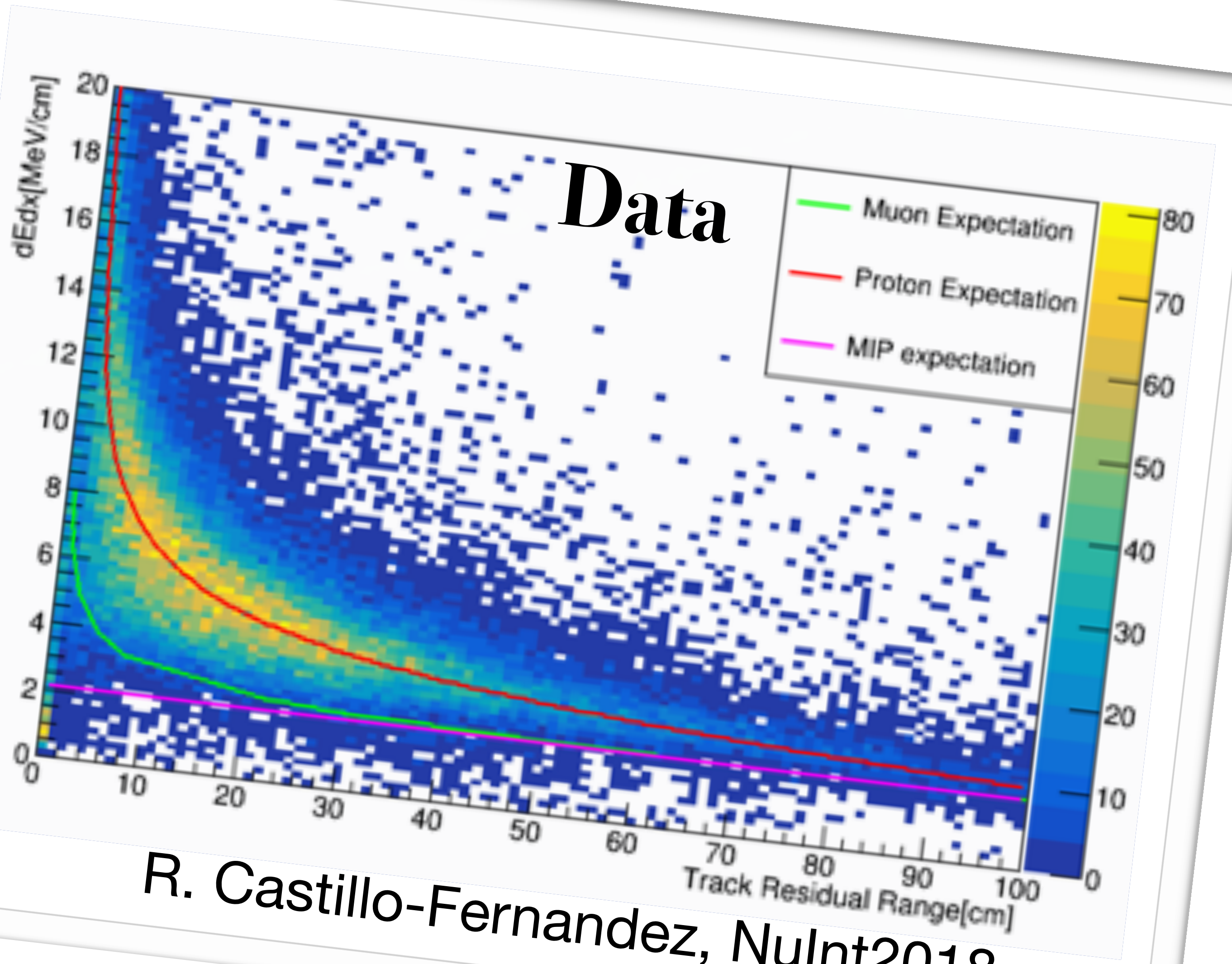




ArXiv:1811.02700, submitted PRD

CCπ^0 Cross Section
- First measurement on Ar
- Test shower reconstruction
- LEE photon backgrounds

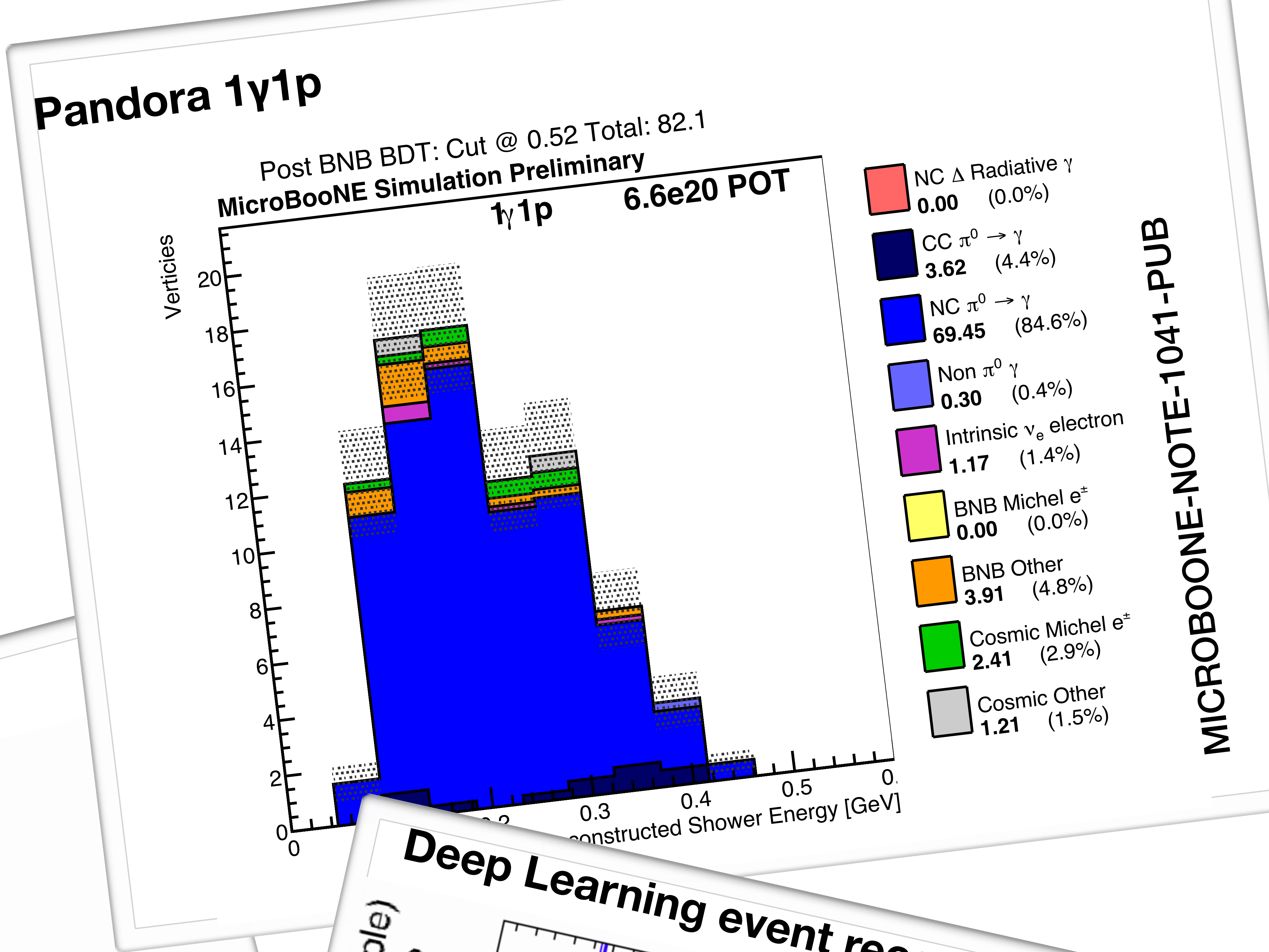
CC1μNp Cross Section
- Proton production
- Proton kinematics
- PID

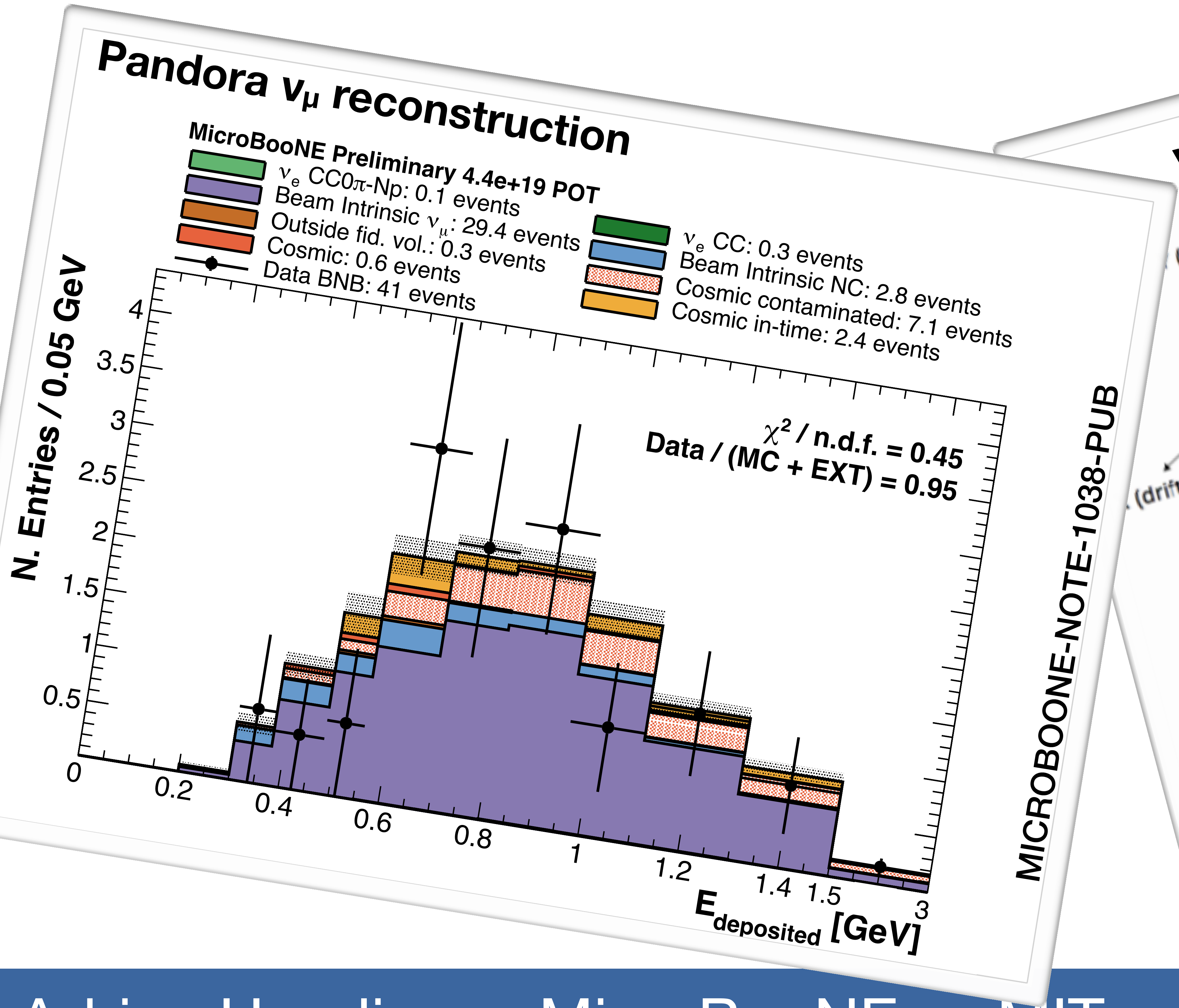


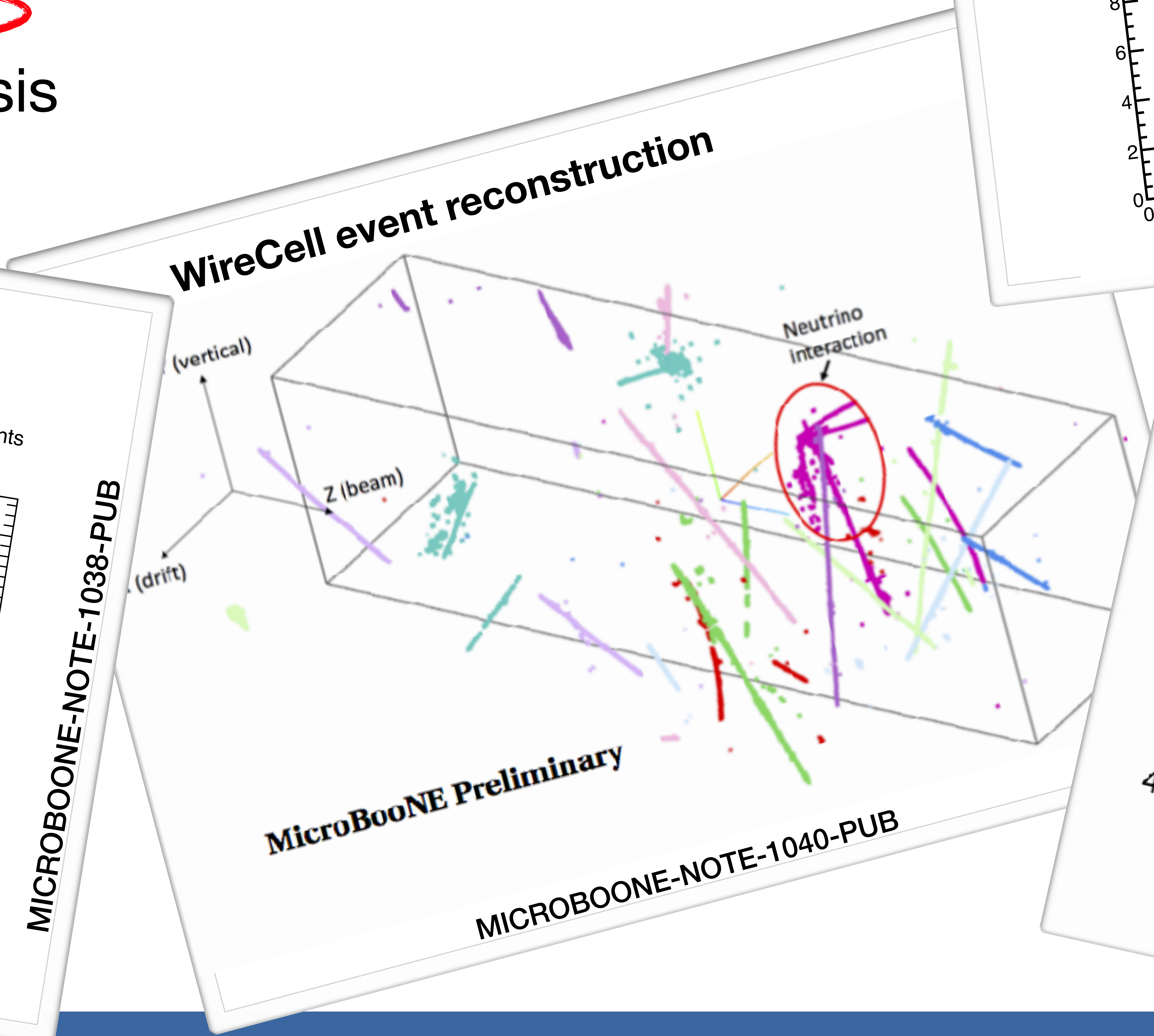
R. Castillo-Fernandez, NuInt2018

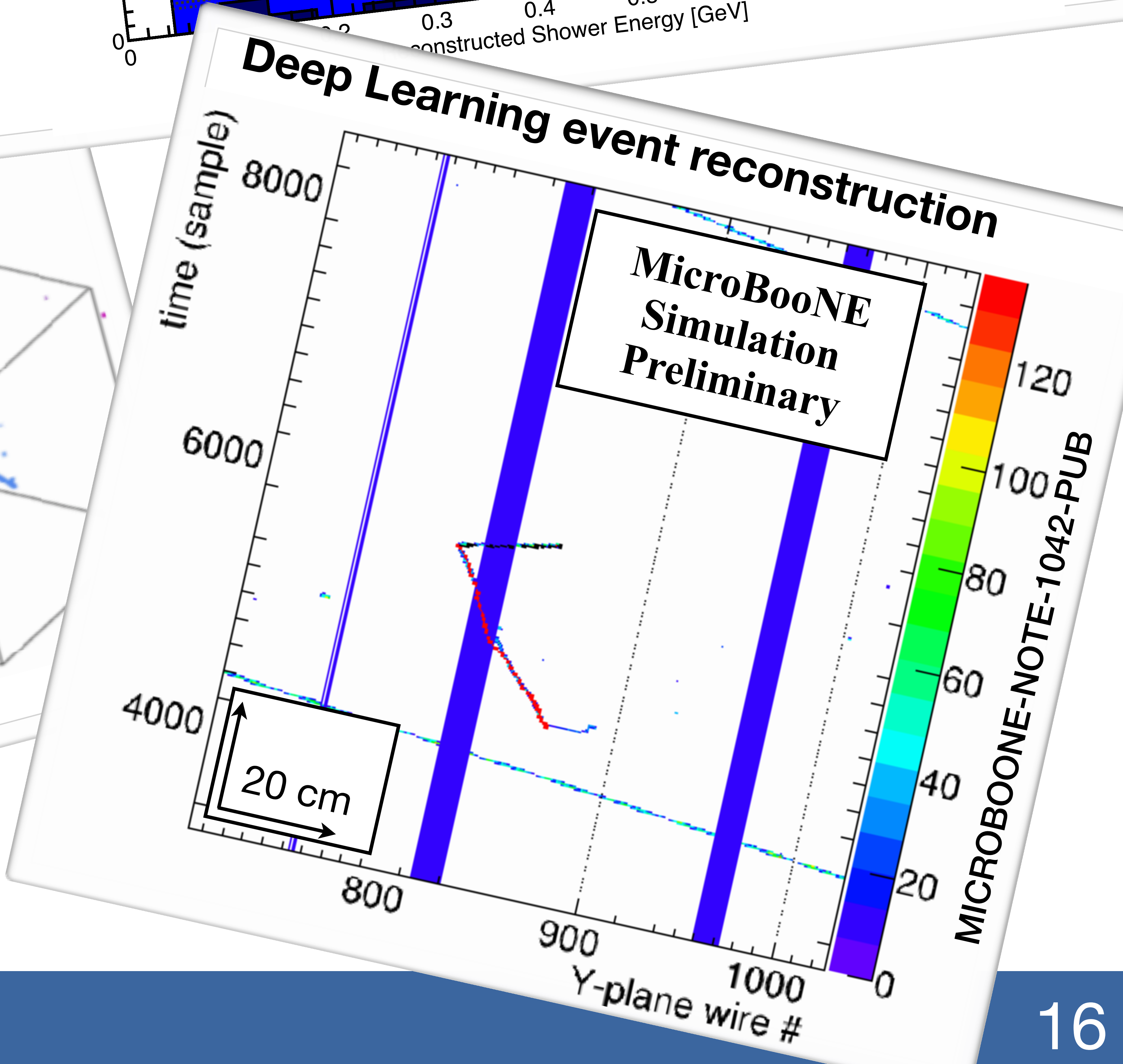
Low Energy Excess Searches

- 4 parallel low energy ν_e-like analysis efforts:
  - Pandora CC0πNP
  - TrajCluster ν_e selection
  - WireCell selection
  - Deep Learning 1l1p
- γ-hypothesis (1γ1p) analysis

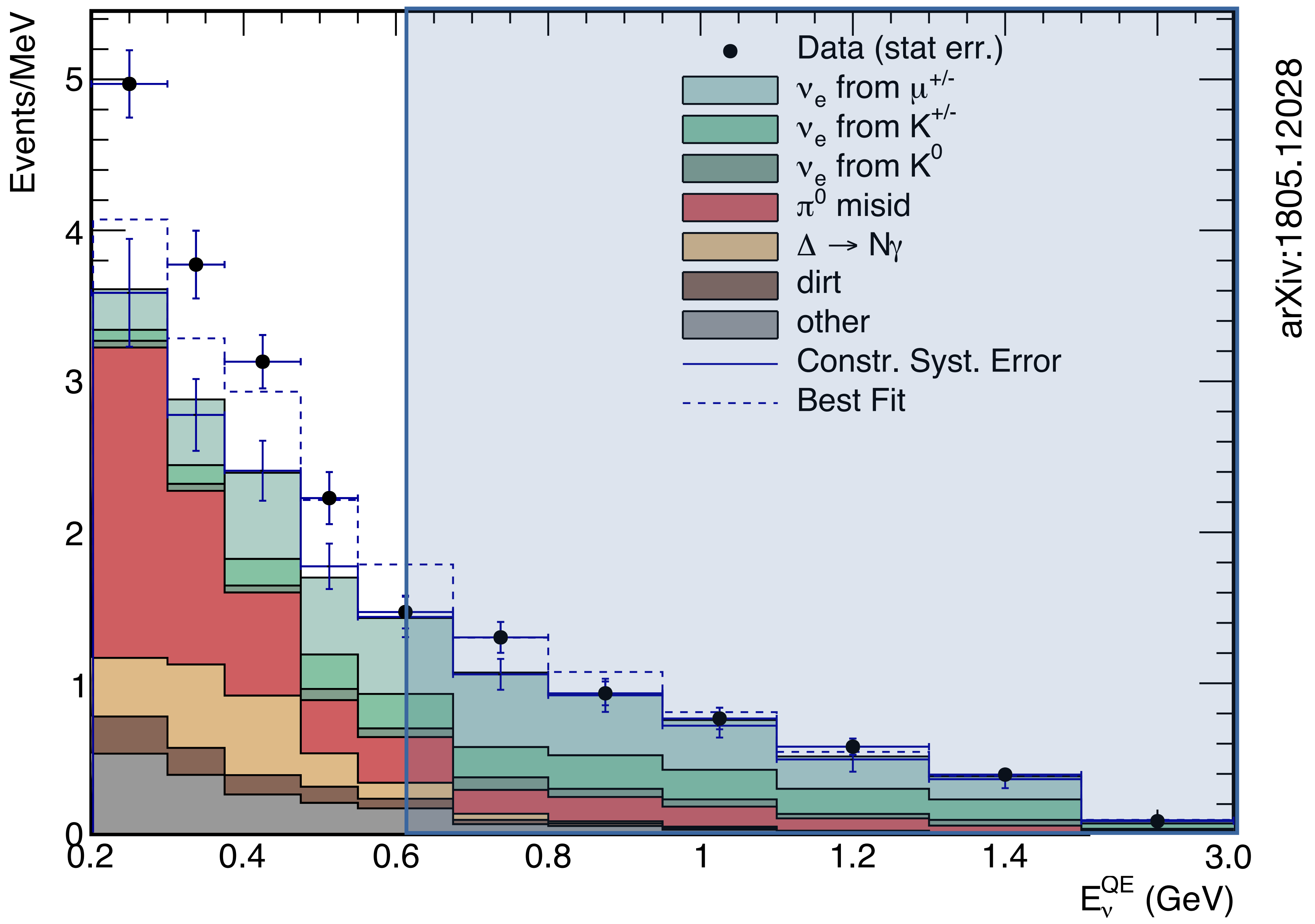


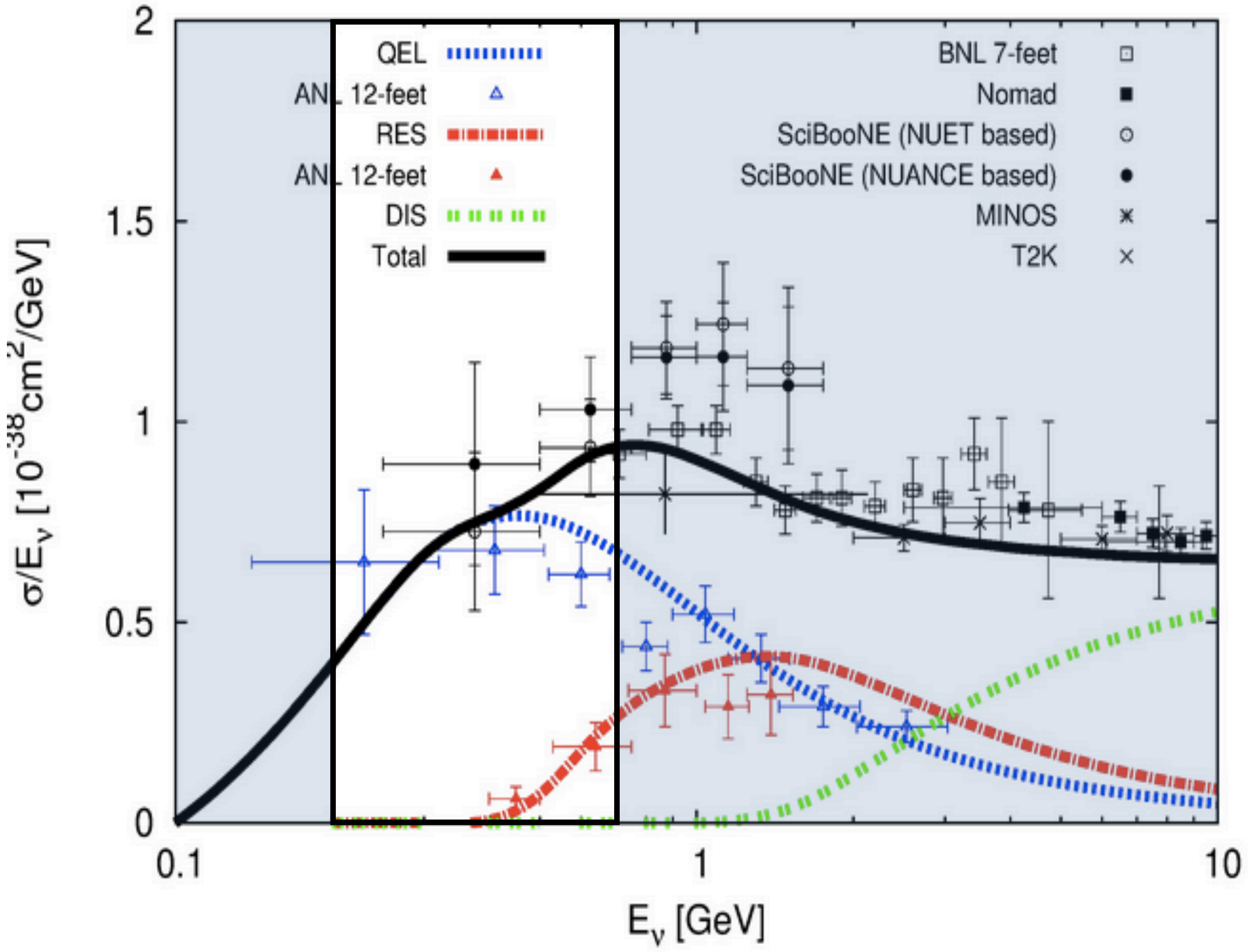


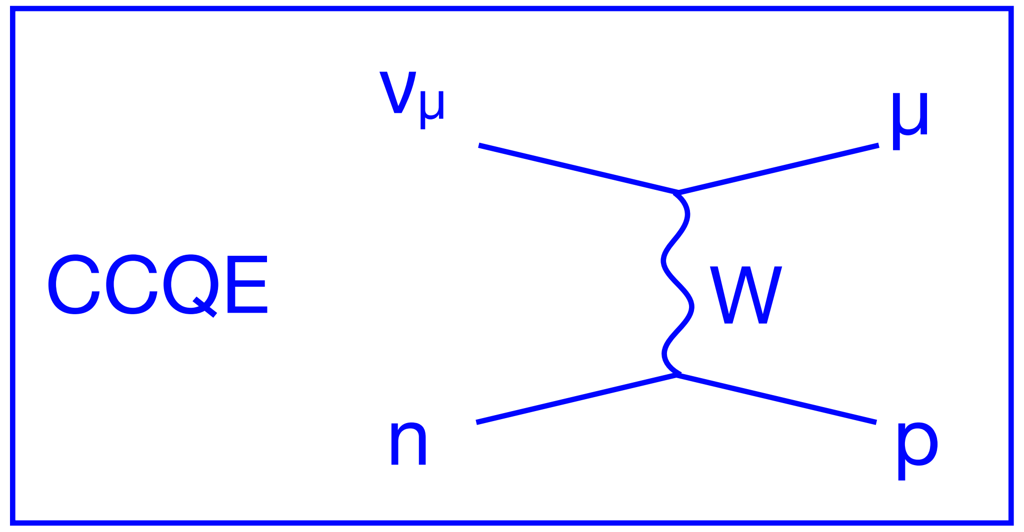


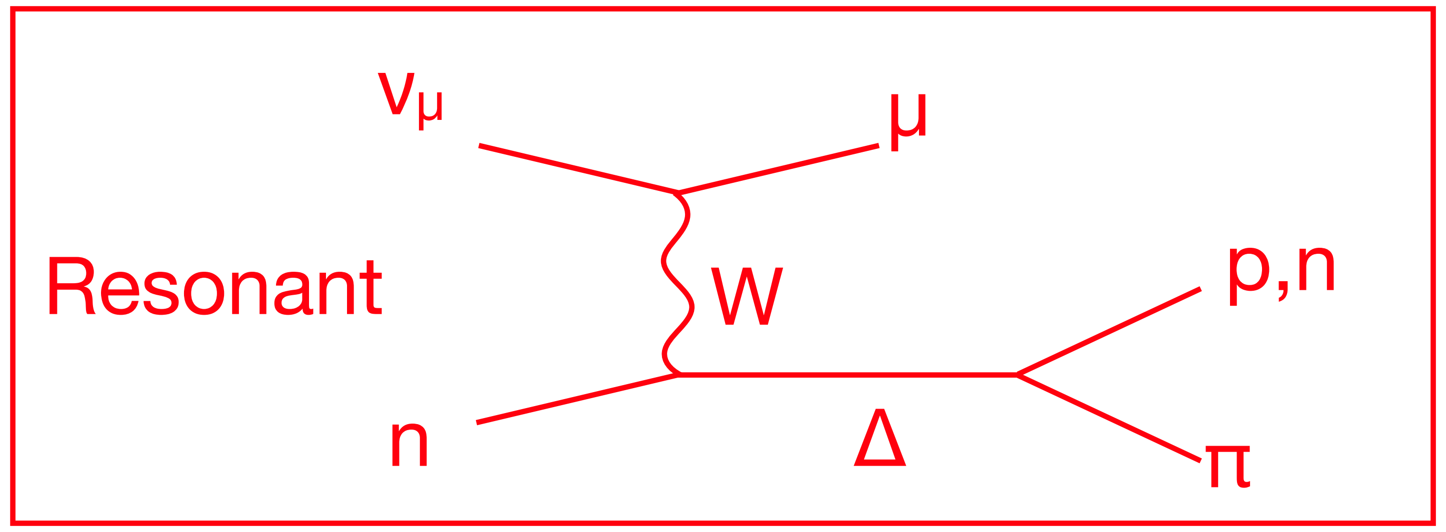


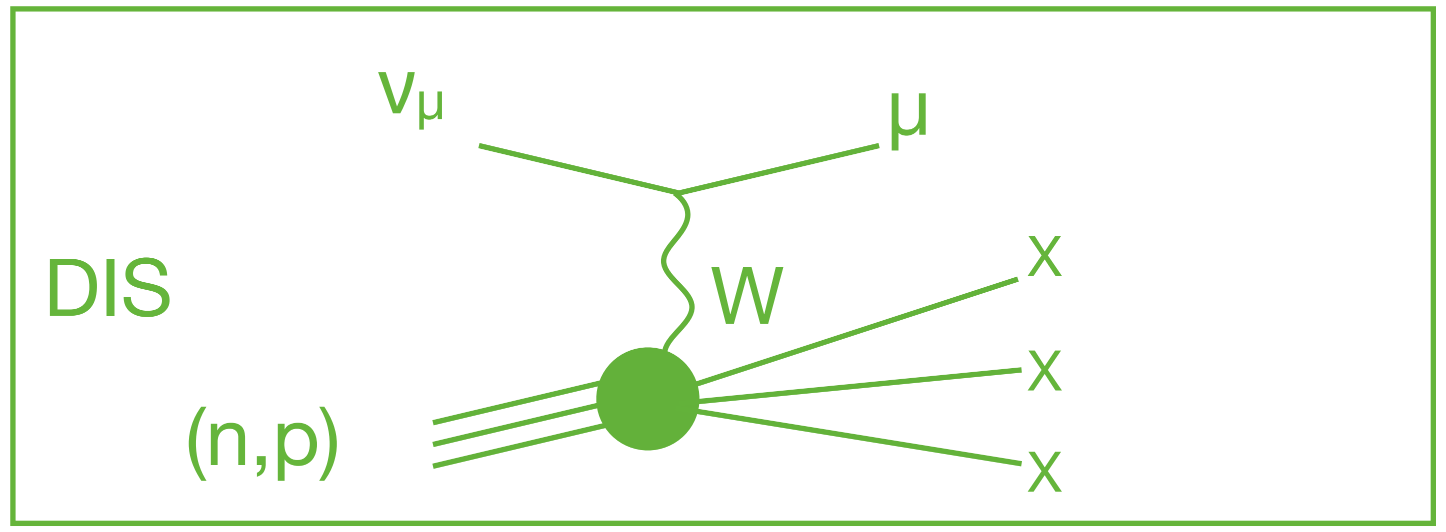
Signal Definition





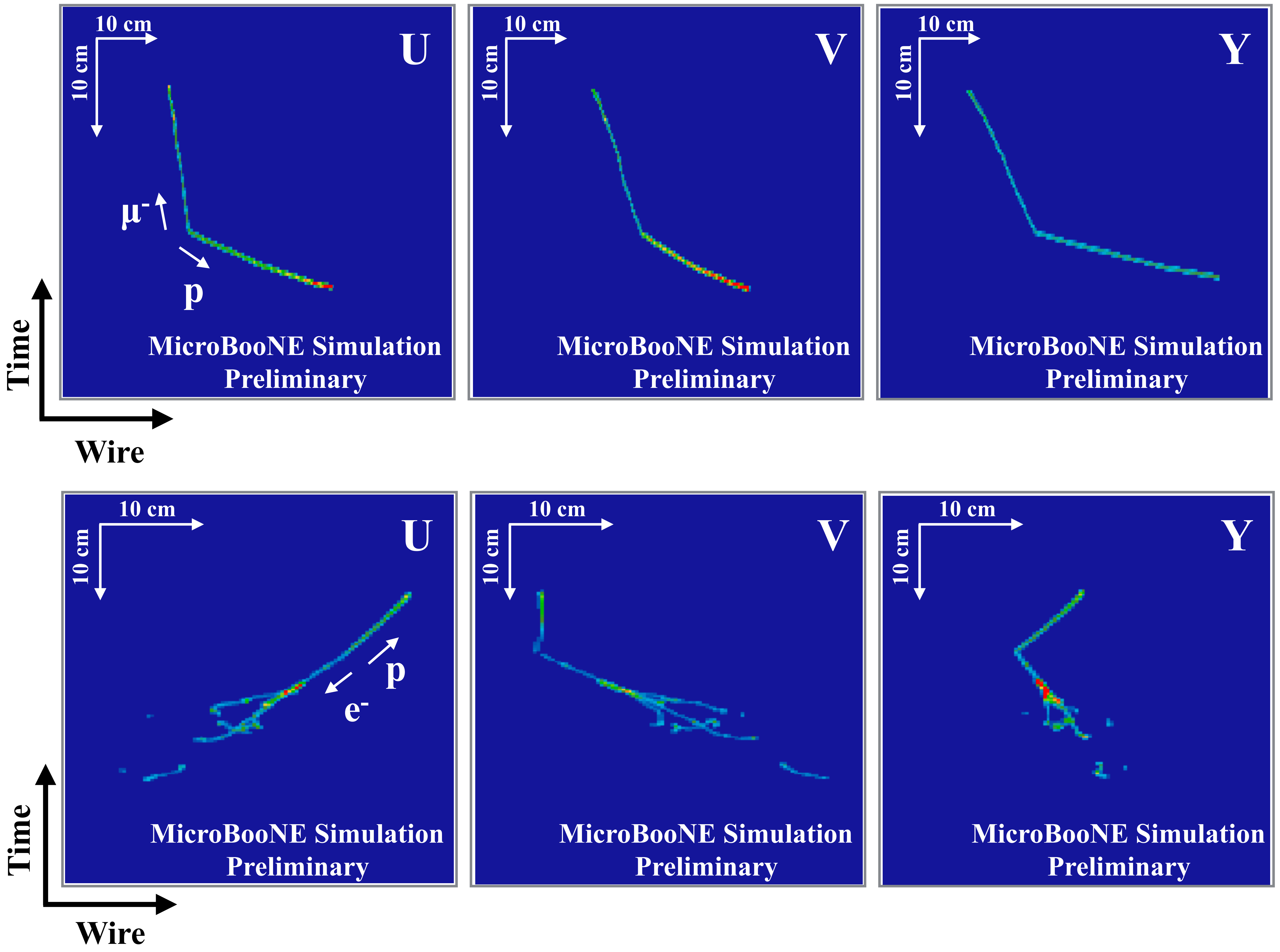






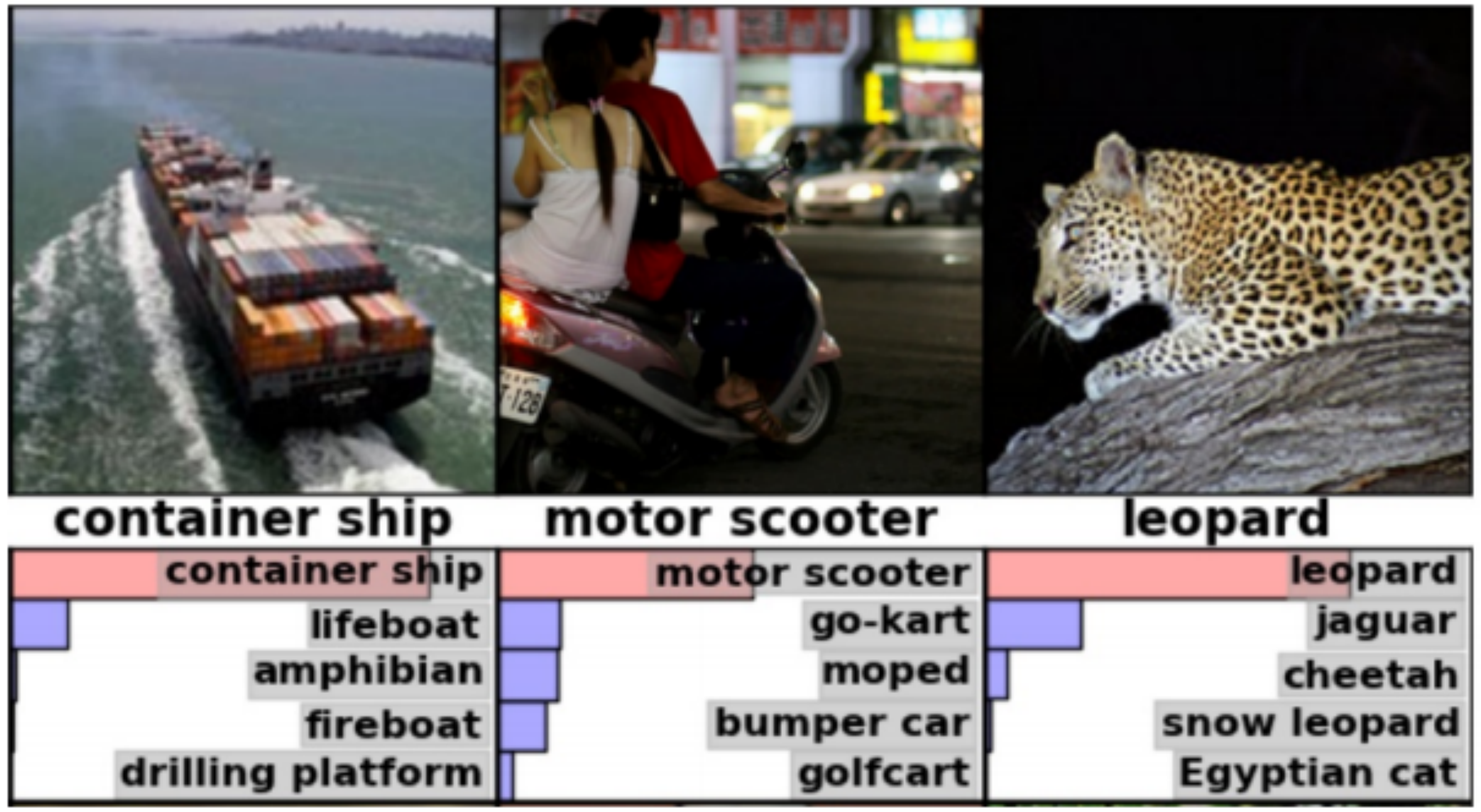
- Excess region at low energy, dominated by CCQE process
- Most events with simple topology

Signal Definition



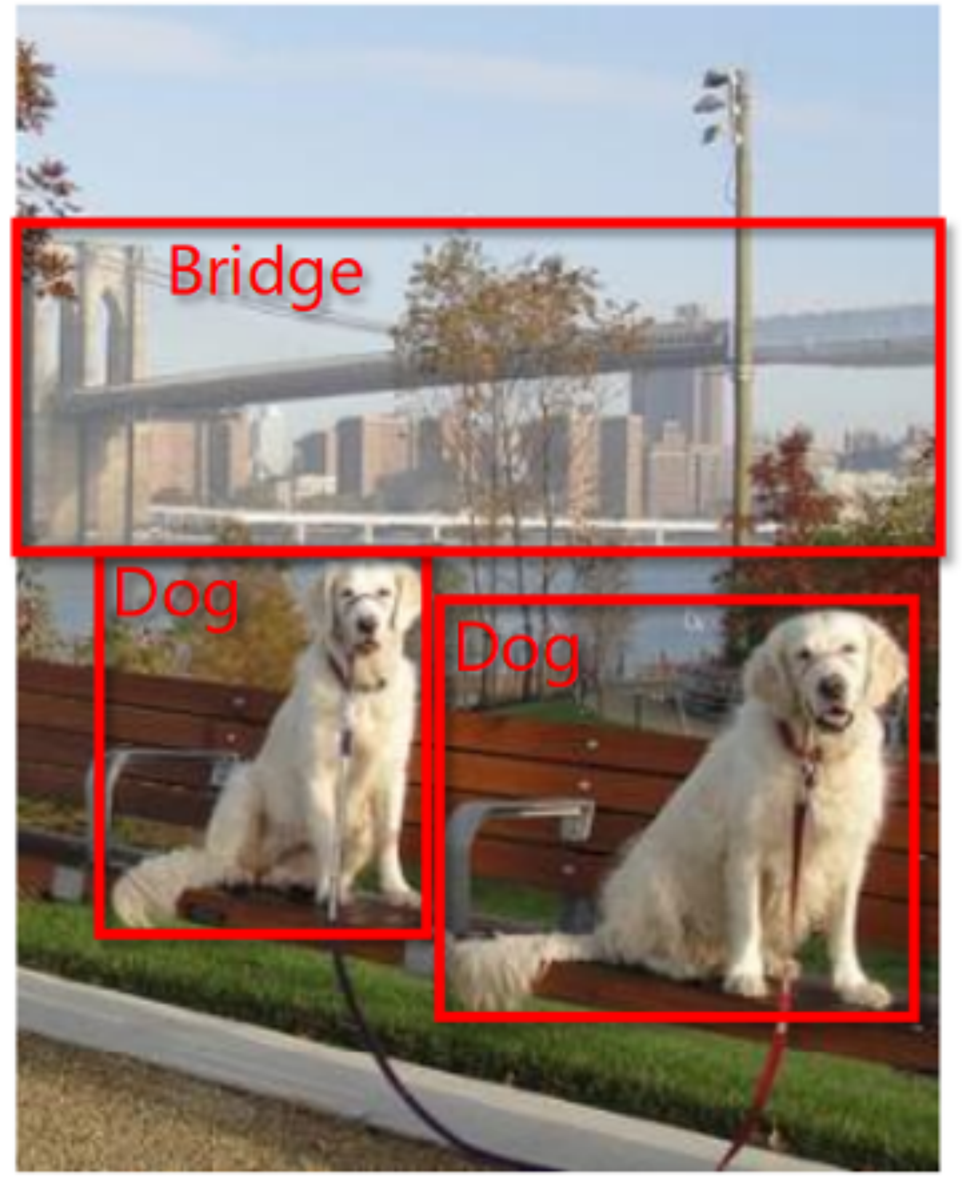
- We will be focusing on a 1 lepton and 1 proton topology:
  - 1 e or μ with KE > 35 MeV
  - 1 p with KE > 60 MeV
  - any number of tracks below threshold
- We will work under the assumption of a CCQE interaction

Machine Learning

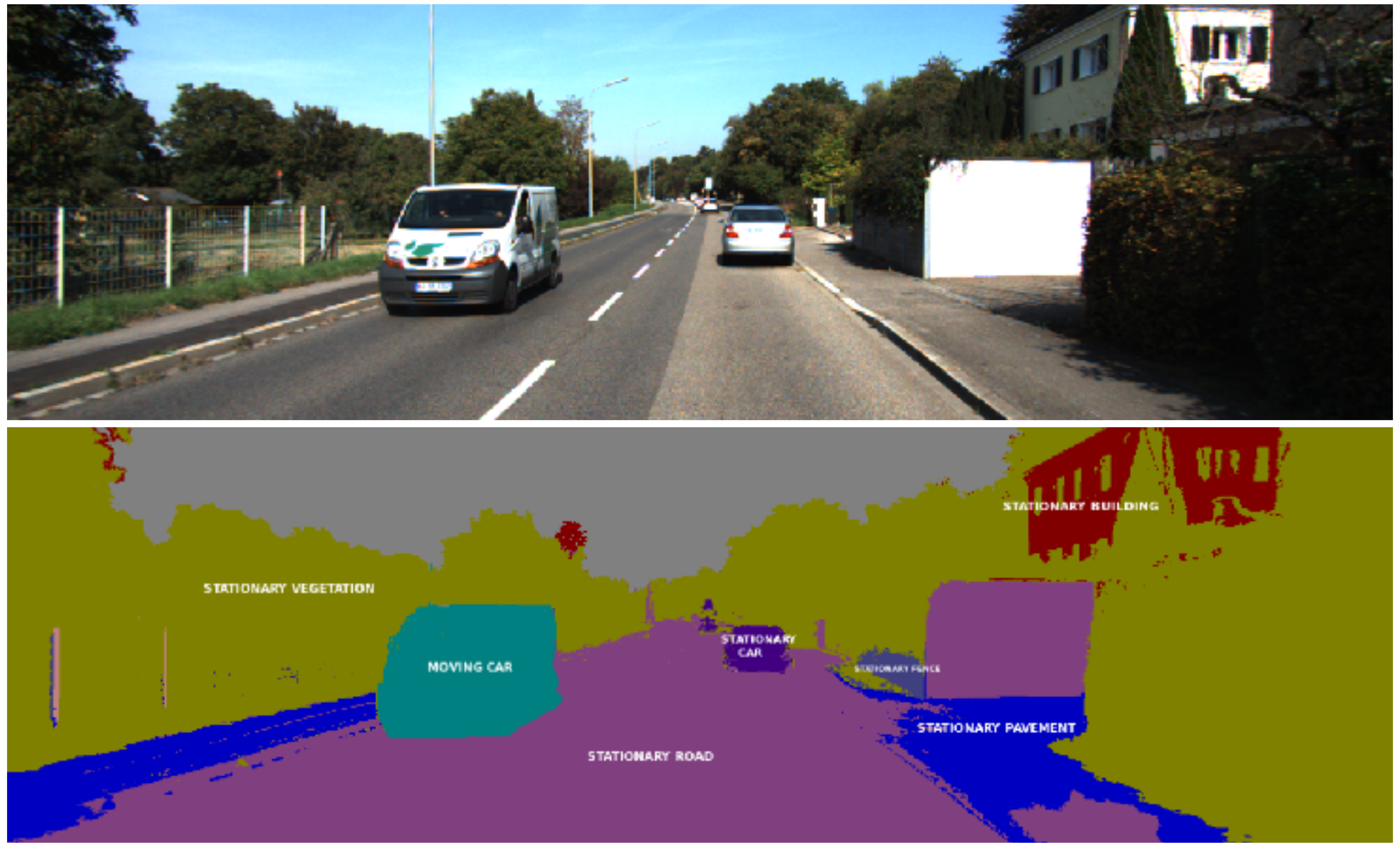


Categorization

Detection

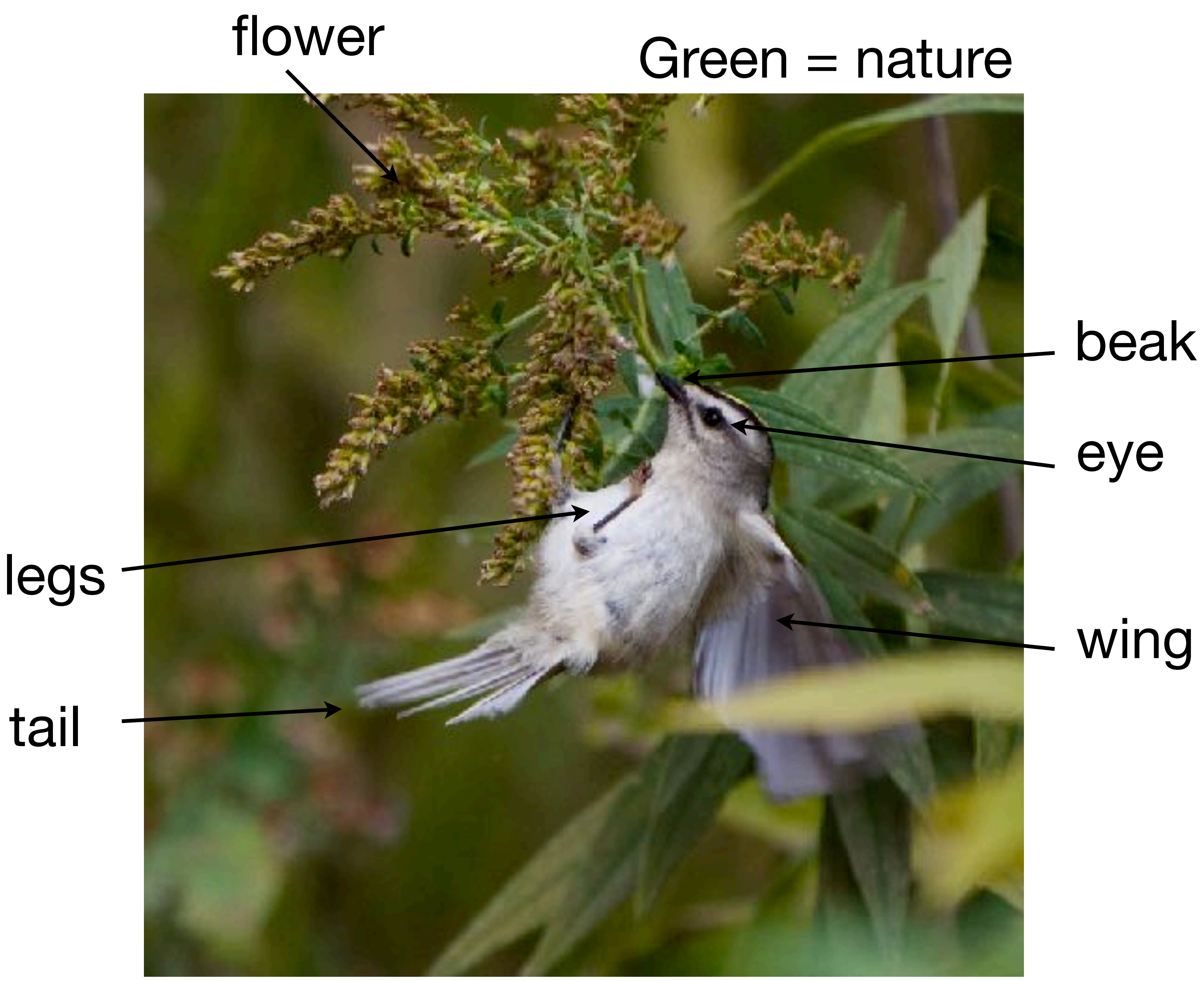


Semantic Segmentation

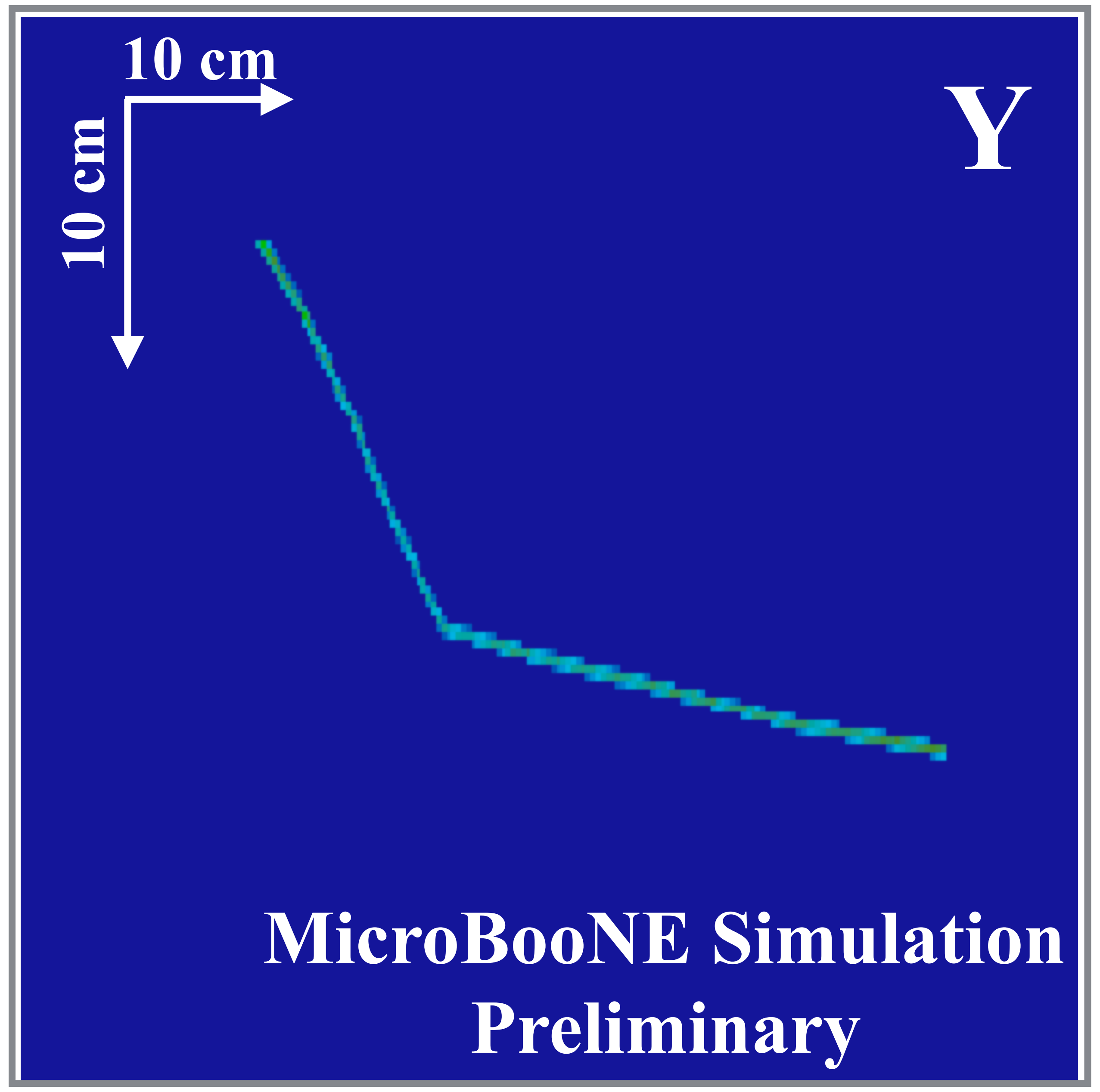


- LArTPCs provide high resolution pictures of neutrino interactions
- Convolutional Neural Networks (CNN) are design to identify content of images (i.e. self driving cars, bio imagery, etc.)
- CNN look for patterns, most basic => more complex

Machine Learning for LArTPC



Bird (Golden-crowned kinglet)

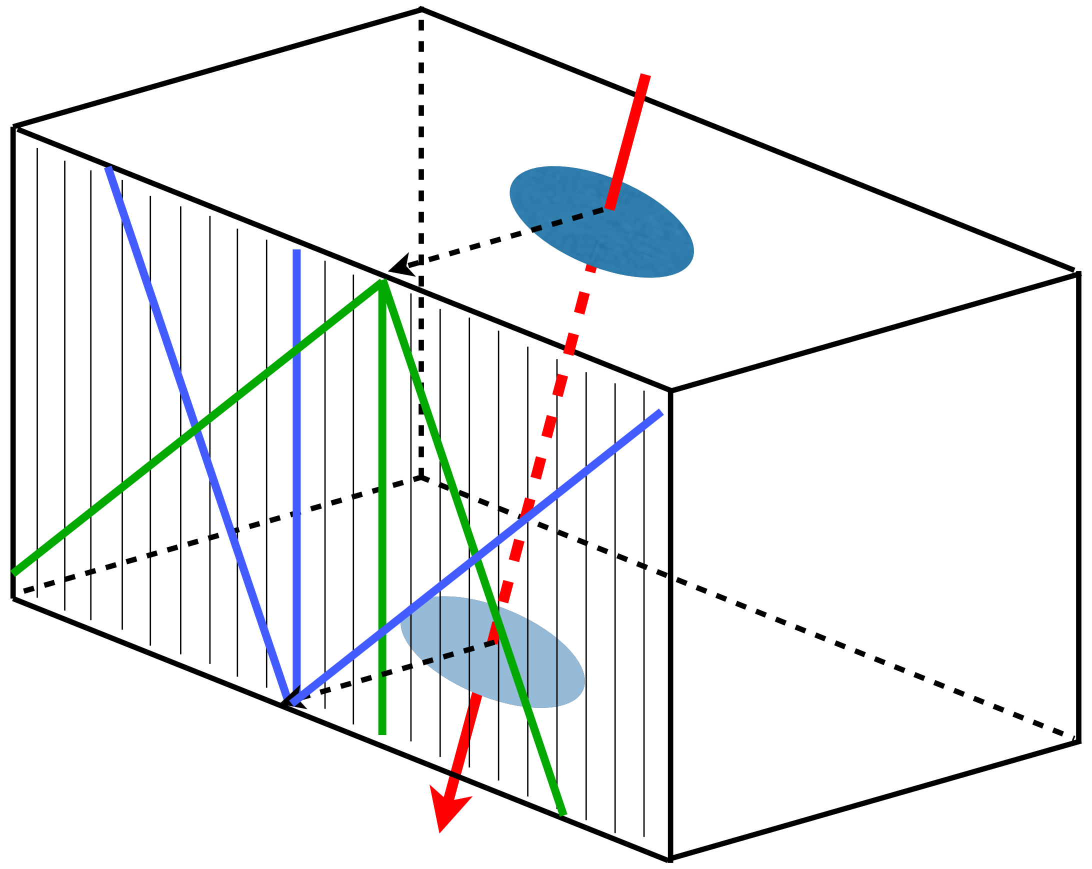


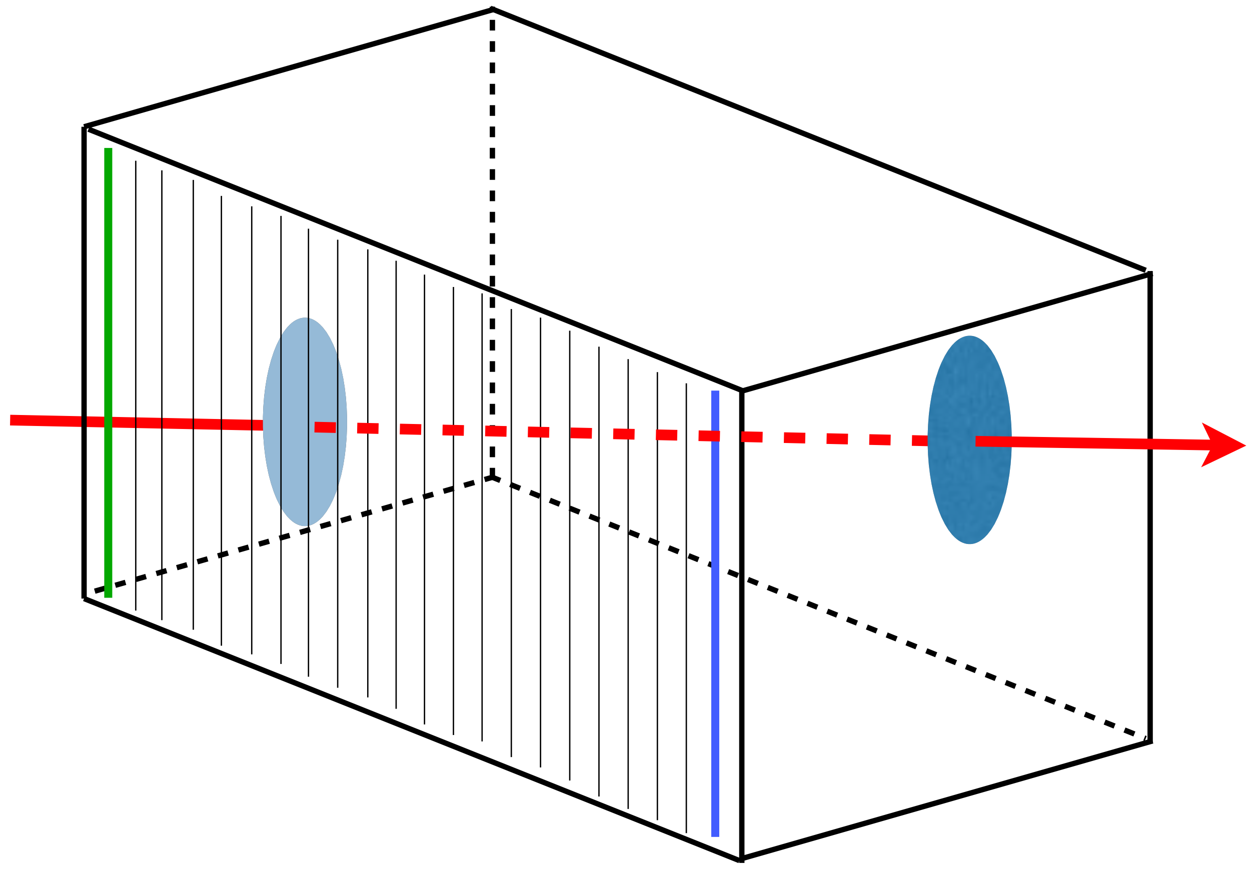
- CNNs look for patterns, pattern associations on rich images
- LArTPCs images are mostly empty (99% of pixels are empty)
- Neutrinos interactions are a small fraction of the total image
- Particles are mostly **tracks or shower**, without much pattern

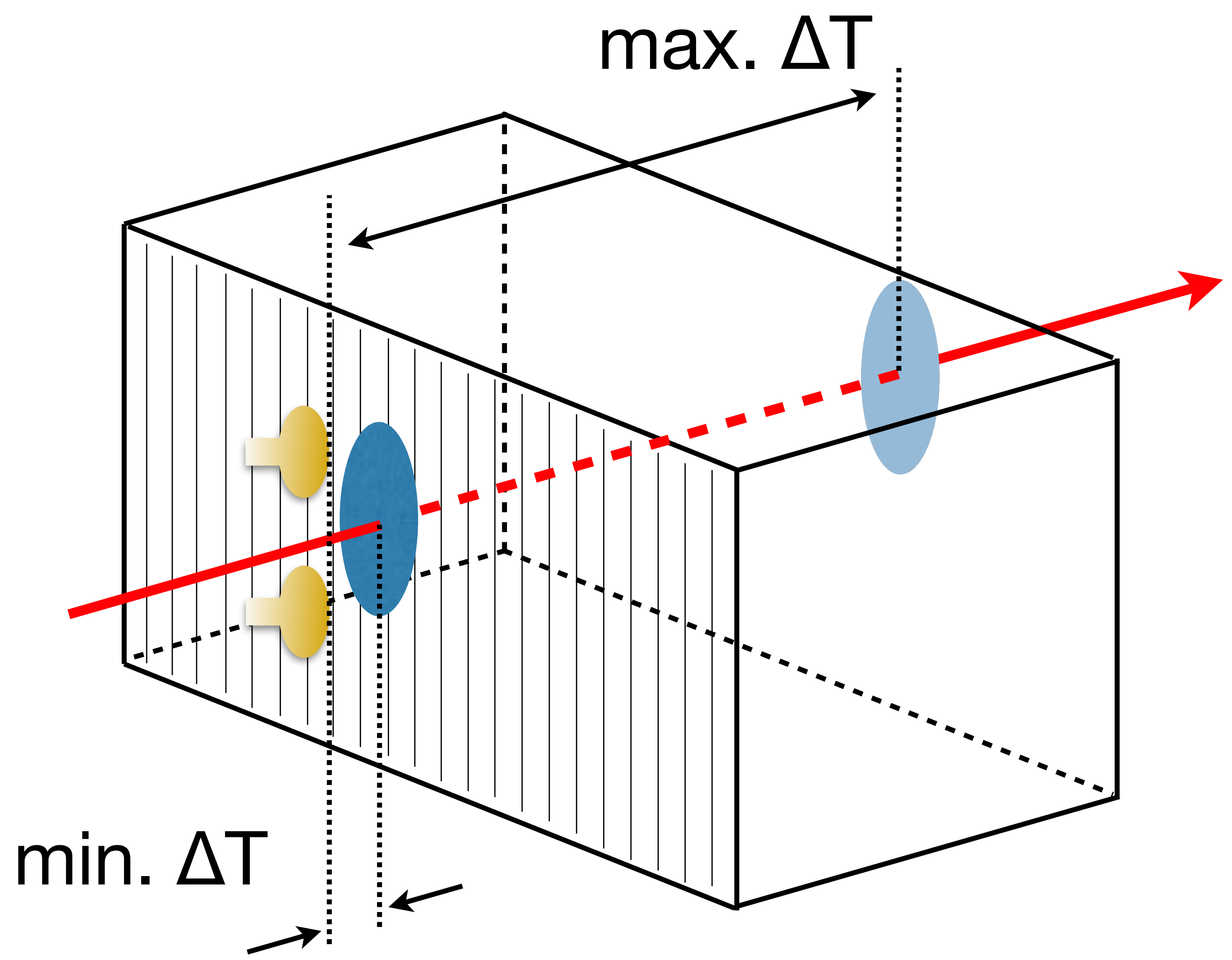
"Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber" JINST 12, P03011 (2017)

Analysis Chain

Cosmic Tagger

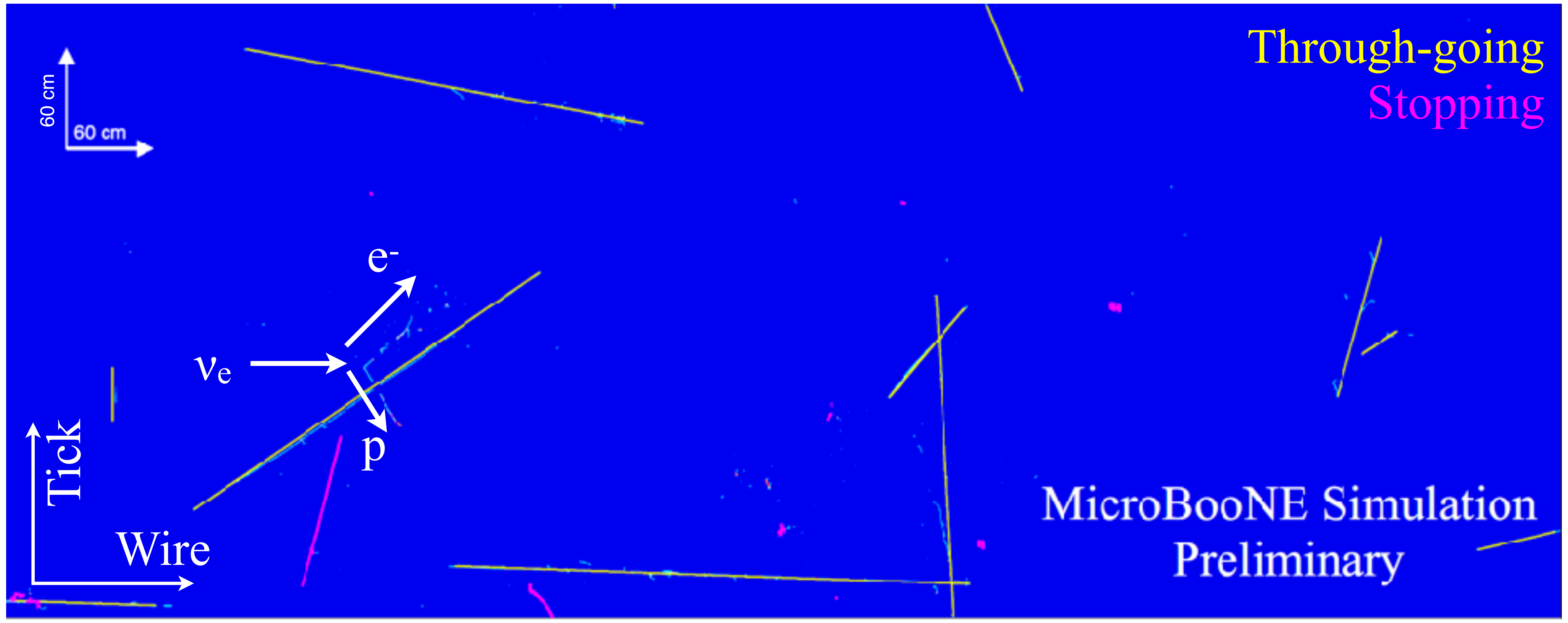

(1)


(2)

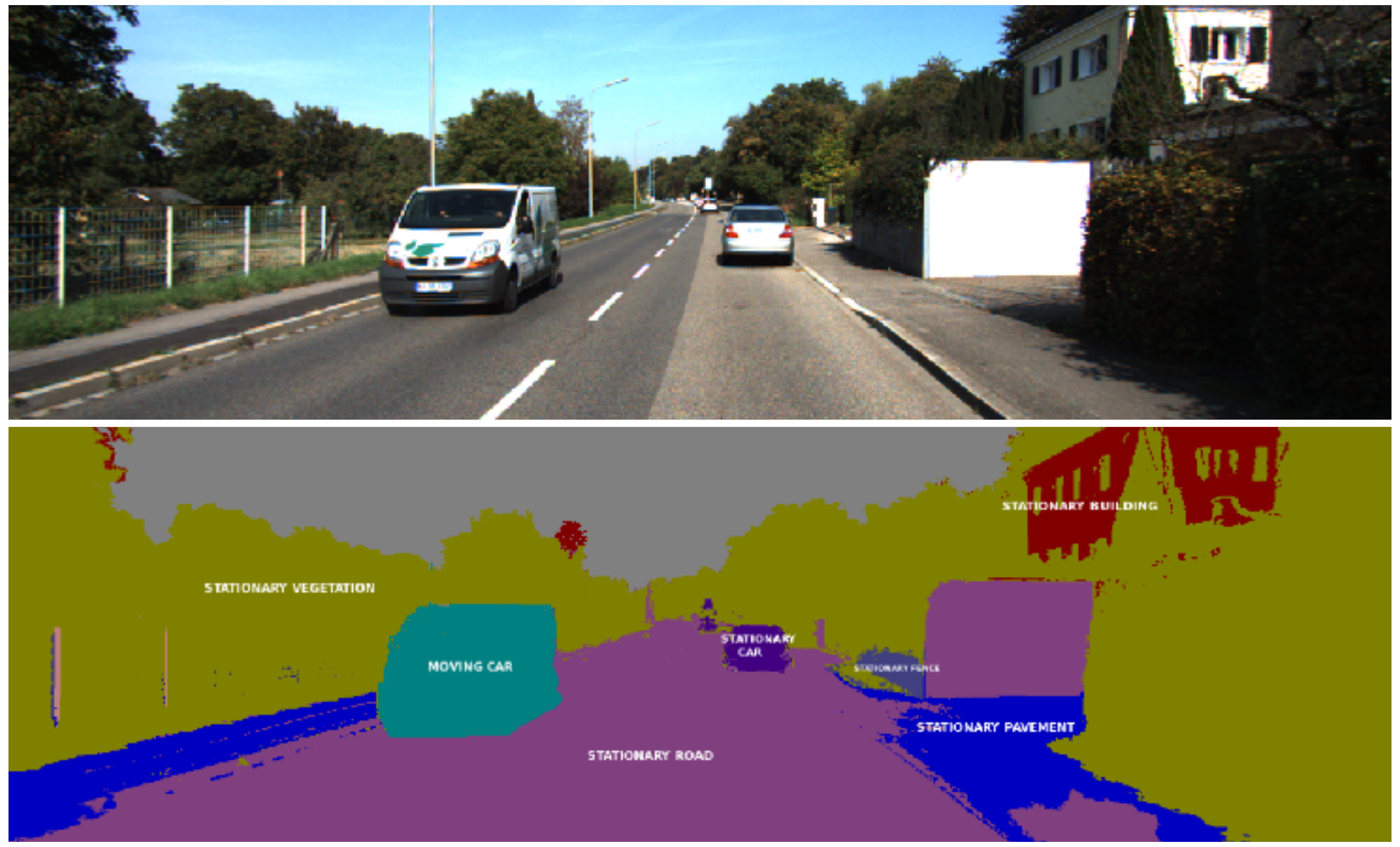


(3)

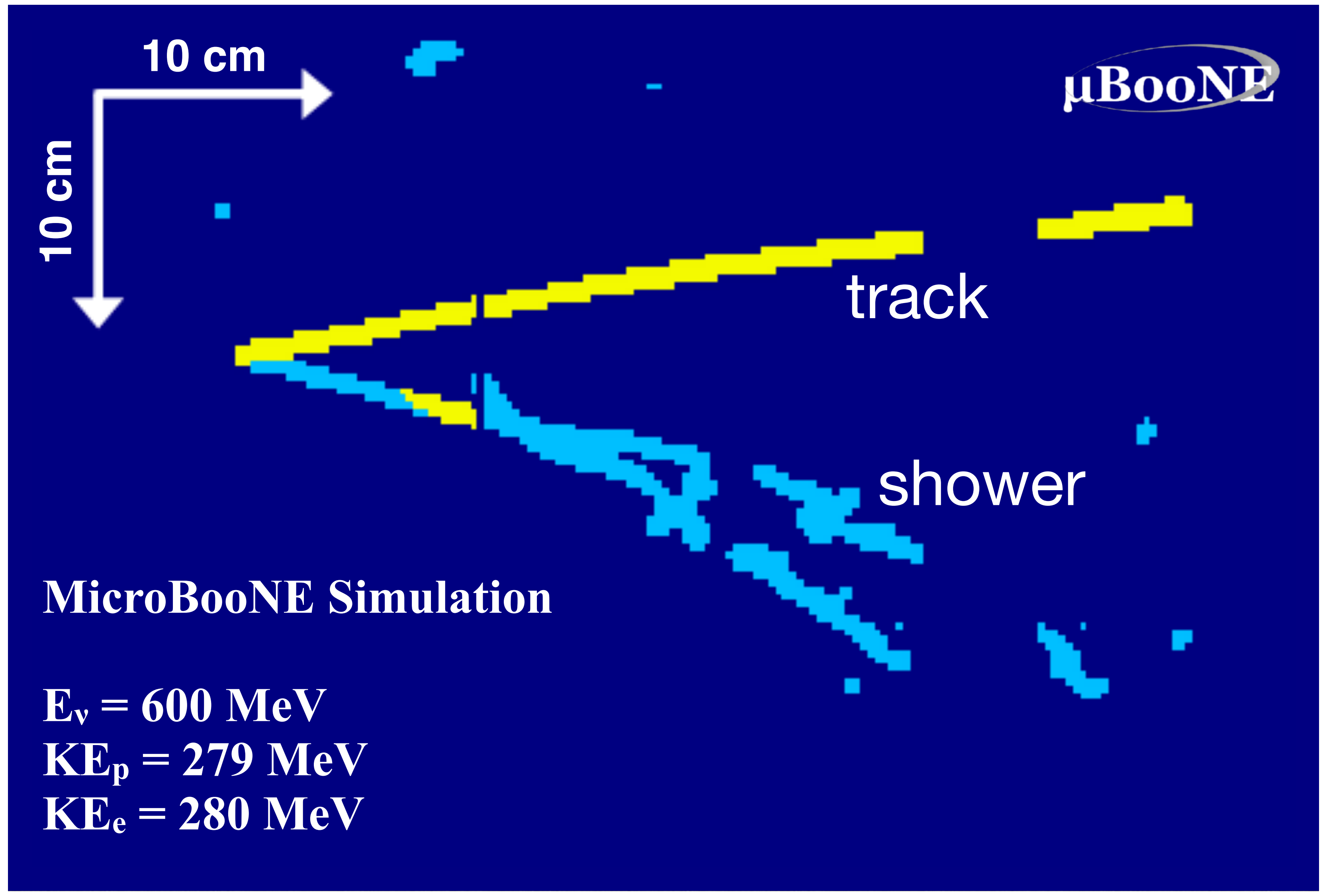
- Follow the charge distribution from one end to the other
- Tracks with only one exit point are labelled as "stopping muons"
- Only "contained" charge remains (no entry/exit point)



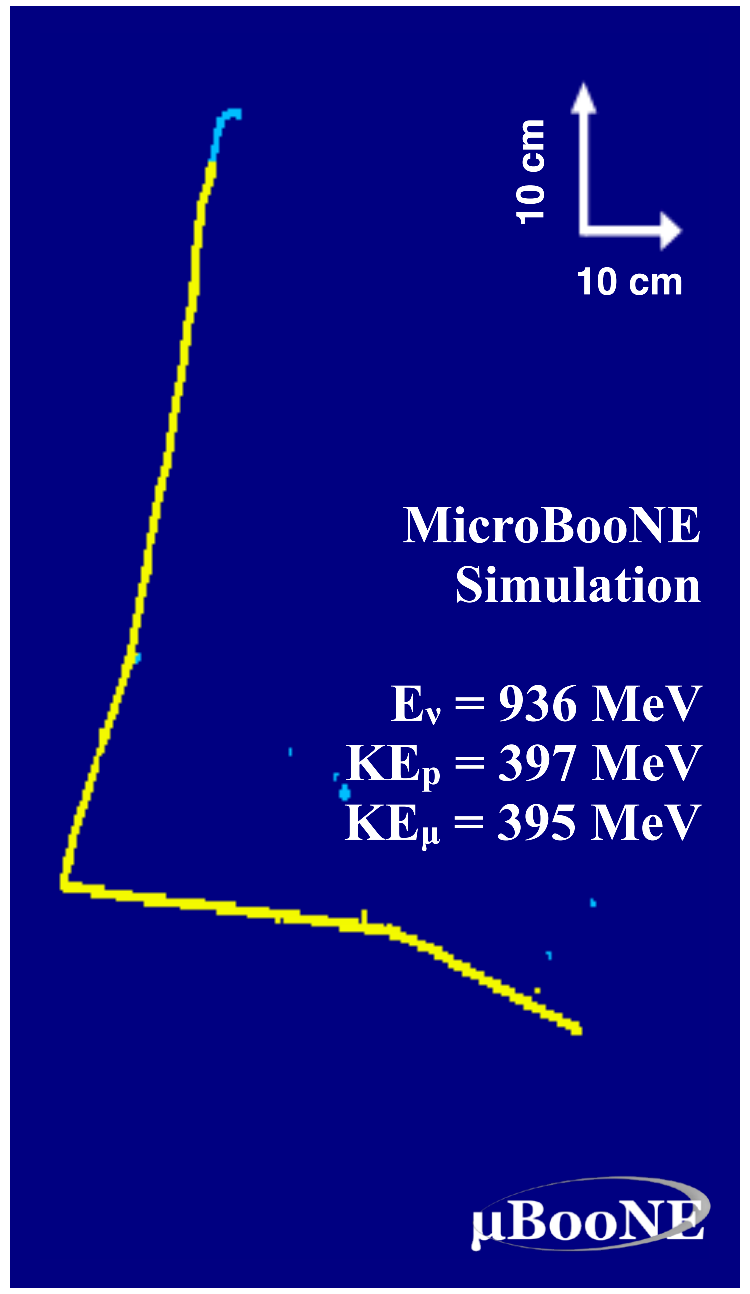
Semantic Segmentation Networks



- SSNets identify the content of an image, and work the convolution chain back to the location of the identified objects
- Pixel-level identification
- Trained to recognize tracks to shower
- Track/shower boundaries can be potential vertex!
- How to validate such network?



MICROBOONE-NOTE-1042-PUB

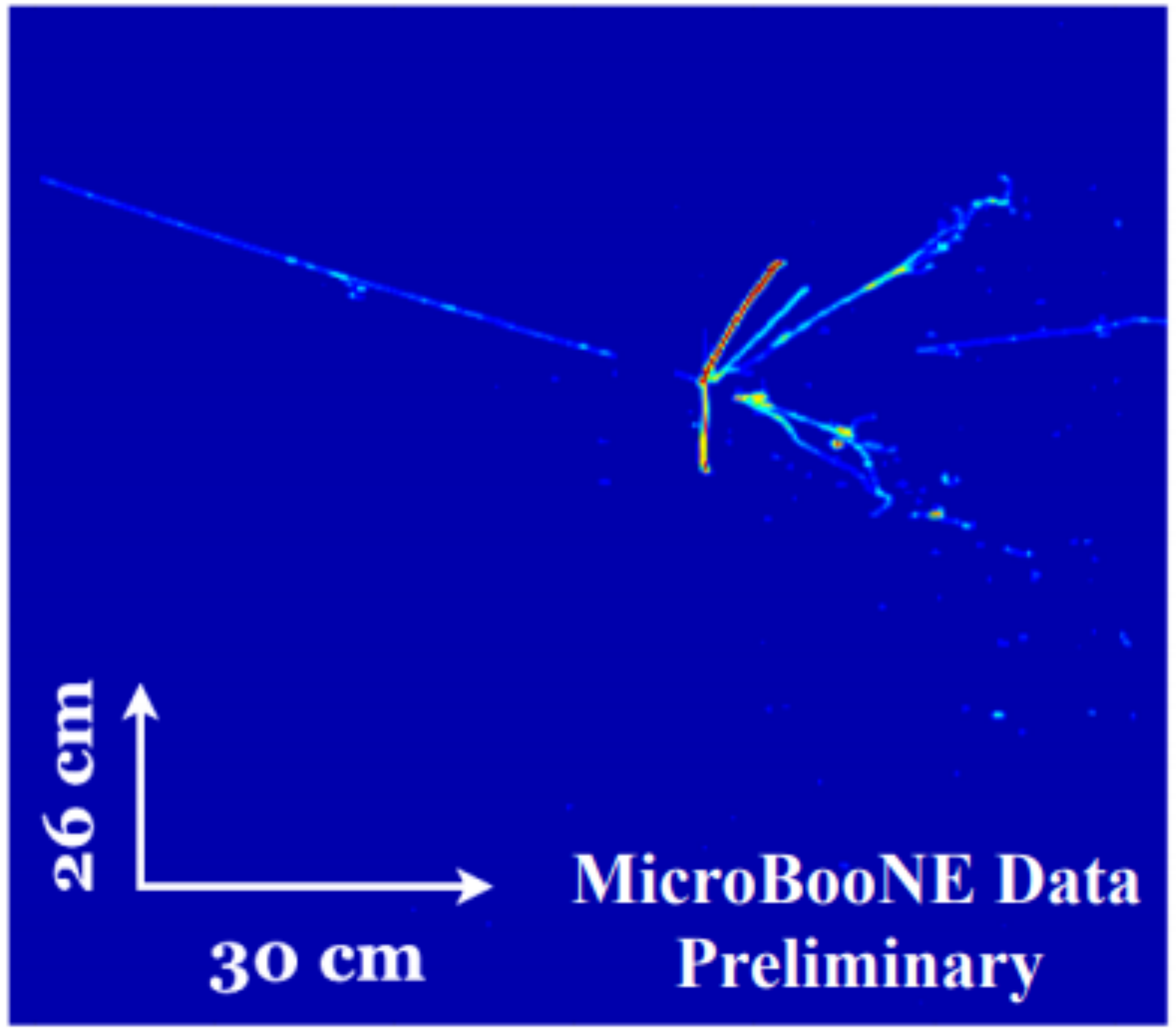


MICROBOONE-NOTE-1042-PUB

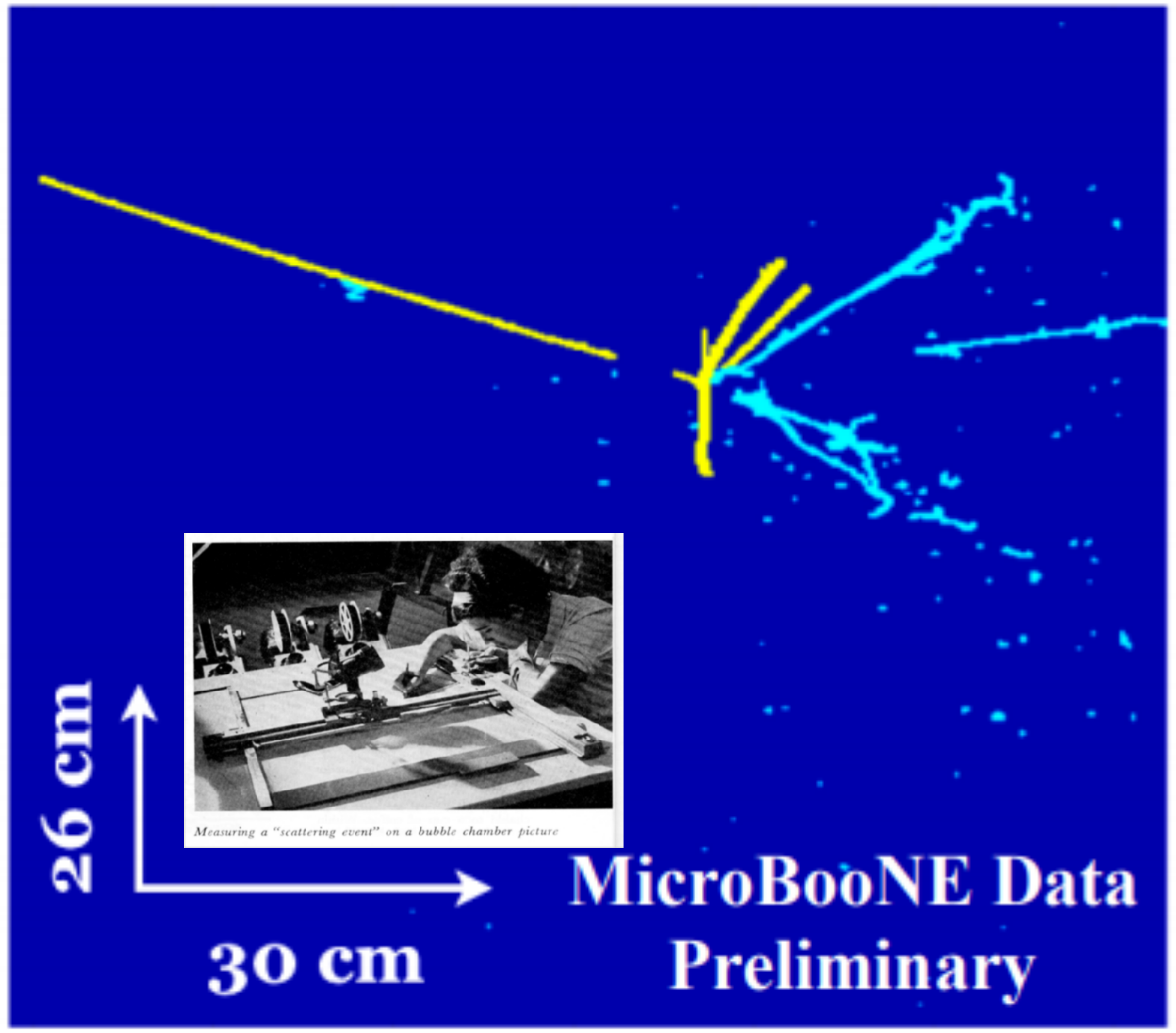
Network on Data

- Network trained on a simulation sample to identify tracks and showers
- Run on a data sample (selection of ν_μ $CC\pi^0$ events)
- "Truth" labelled by a trained human physicist

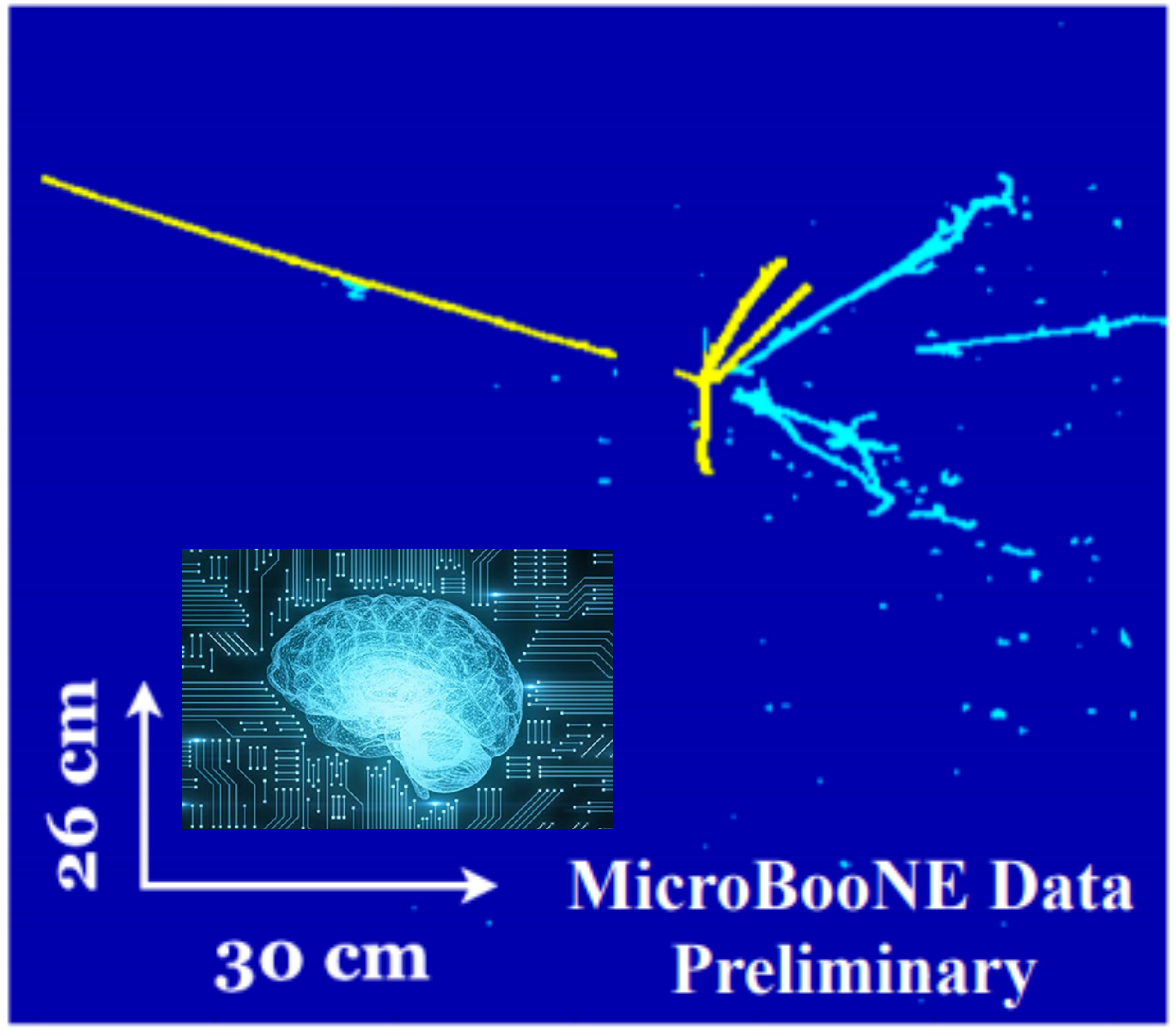
Input Image



Human Labeling

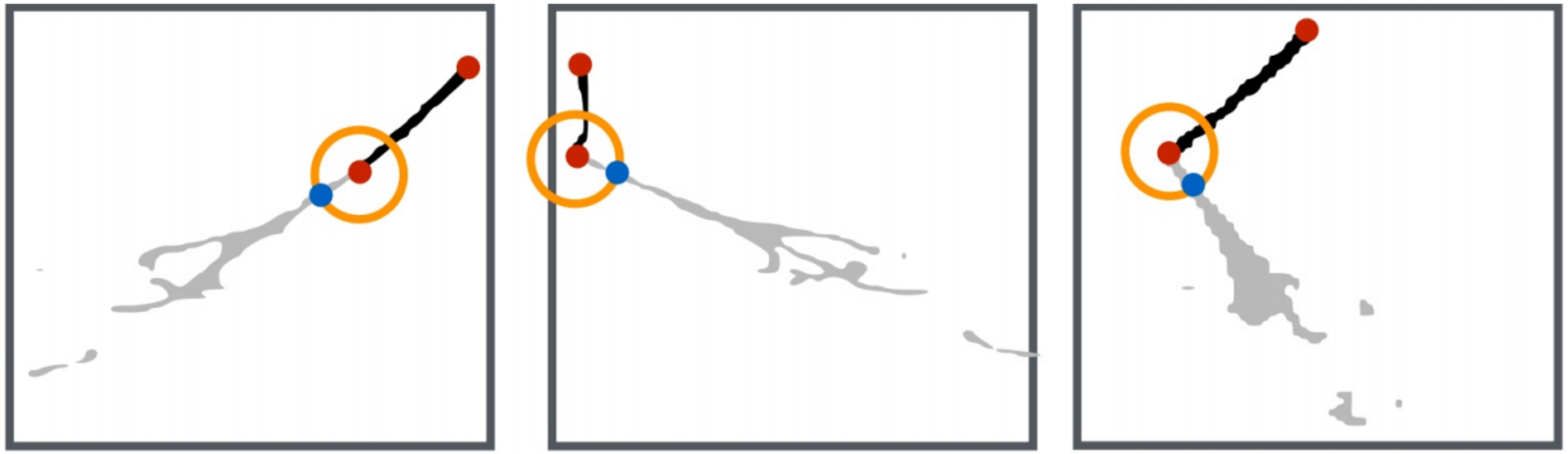


Network Labeling



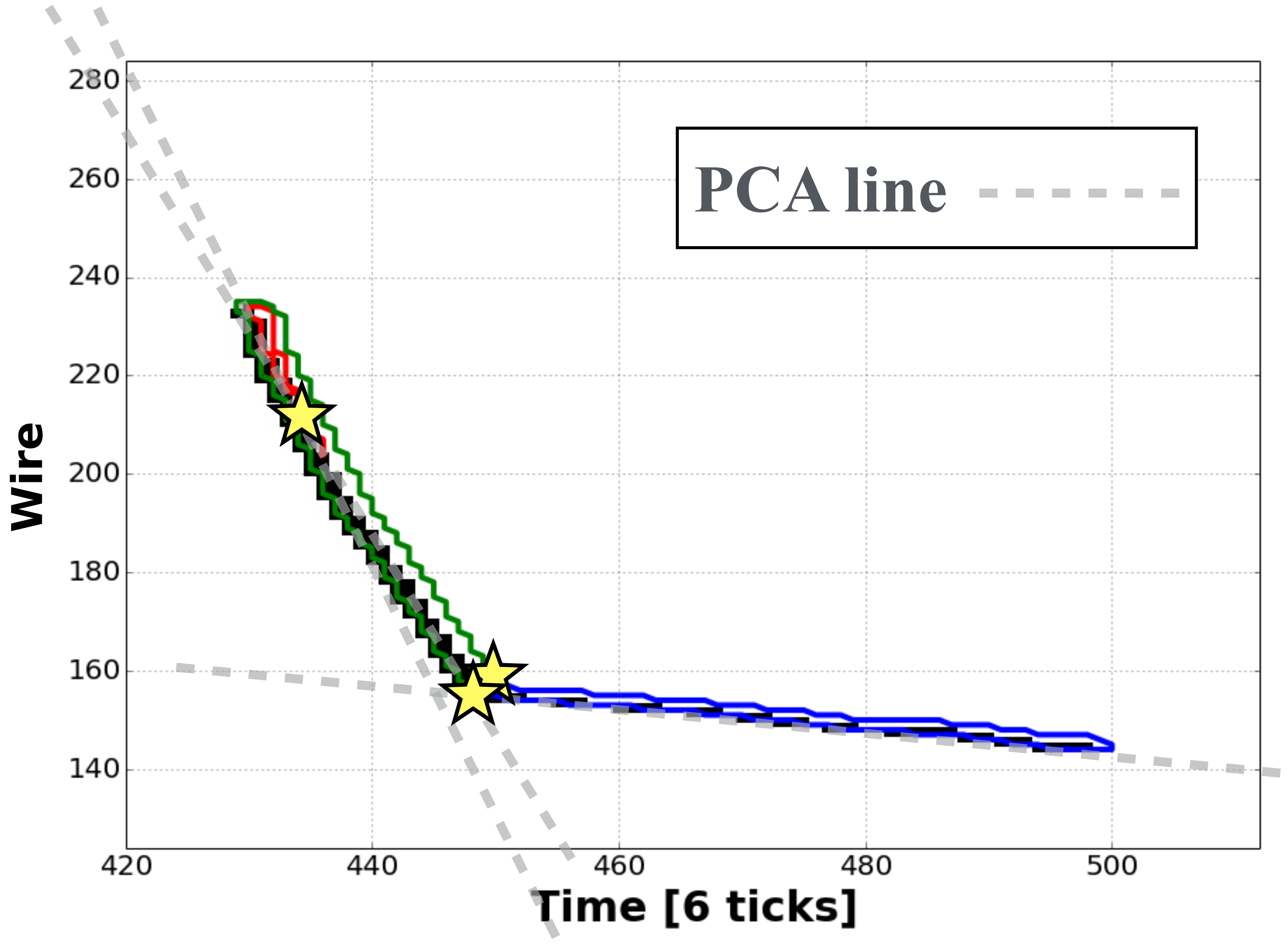
"A Deep Neural Network for Pixel-Level Electromagnetic Particle Identification in the MicroBooNE Liquid Argon Time Projection Chamber " arXiv:1808.07269, submitted to PRD

Vertex Finding



- Identify potential neutrino vertices
- Use SSNet's output track-only and shower-only images
- OpenCV libraries for image processing
- First, identify seeds in each image separately
  - Track/shower boundary
  - Kinks on tracks

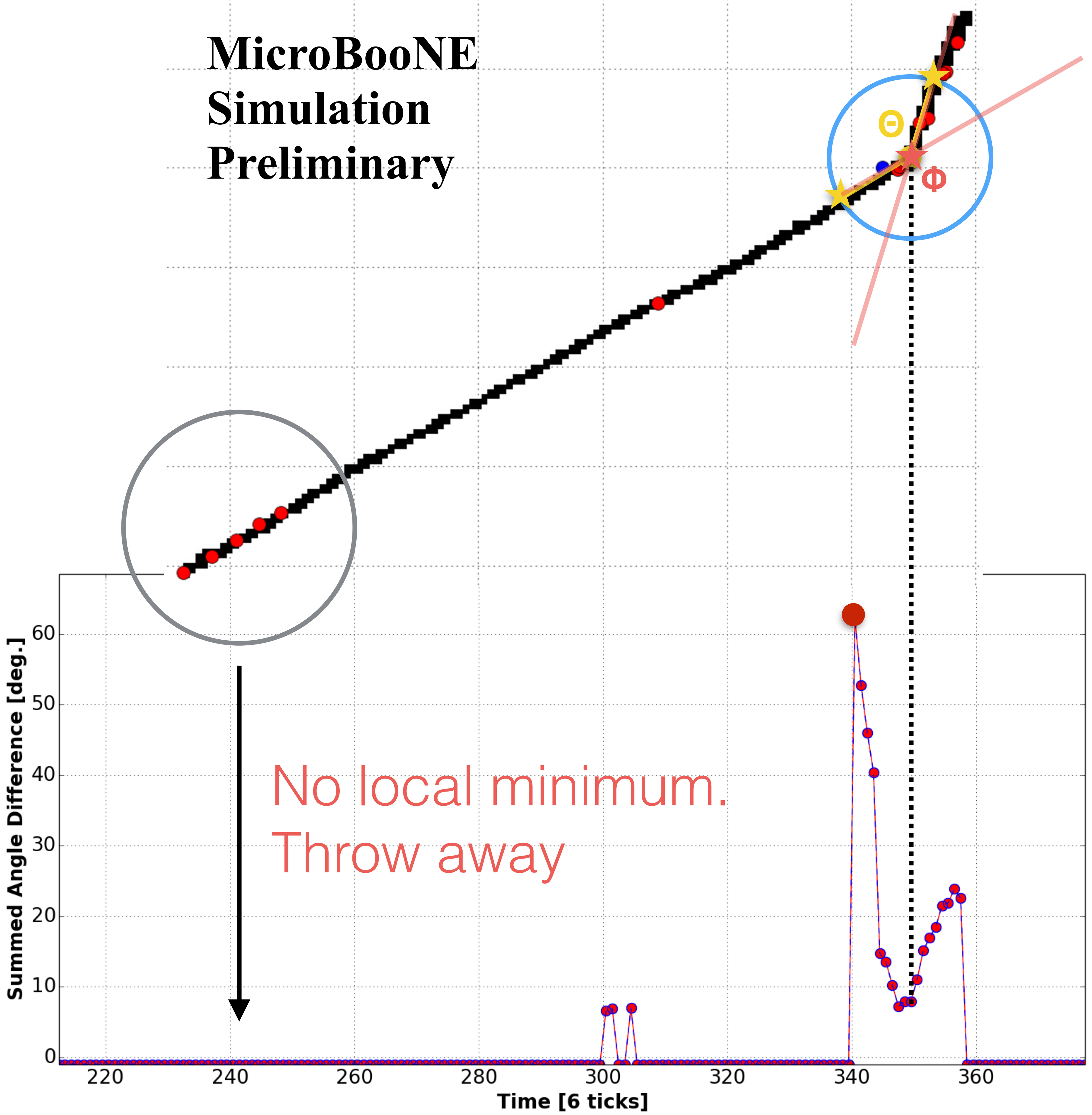
Vertex Seeds

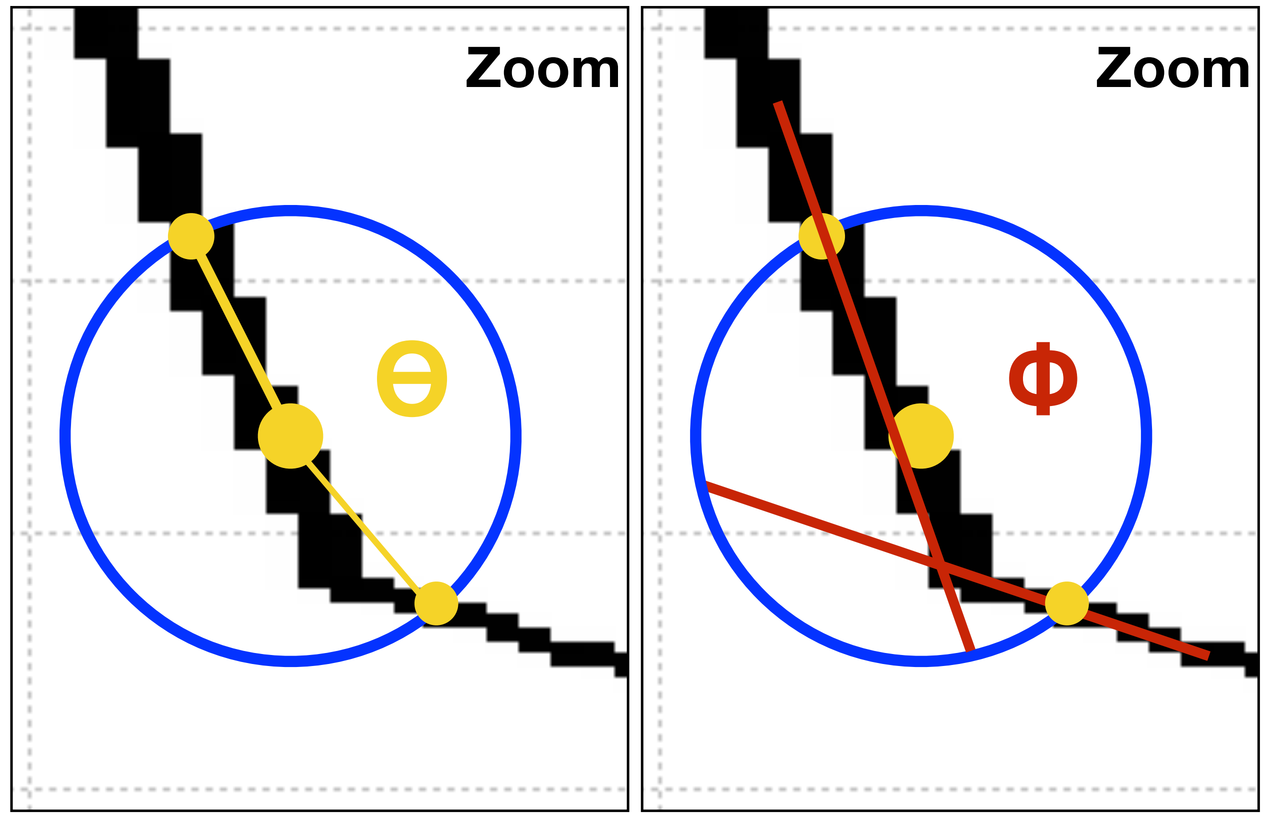


- Break down the track-only pixel cluster in sub-clusters :
  - High-Charge / Low-Charge
  - Linear clusters
- Fit each linear clusters by a line (Principal Component Analysis)
- Vertex Seeds are the cluster break-down points and PCA crossing points

Best Seed Position

time →

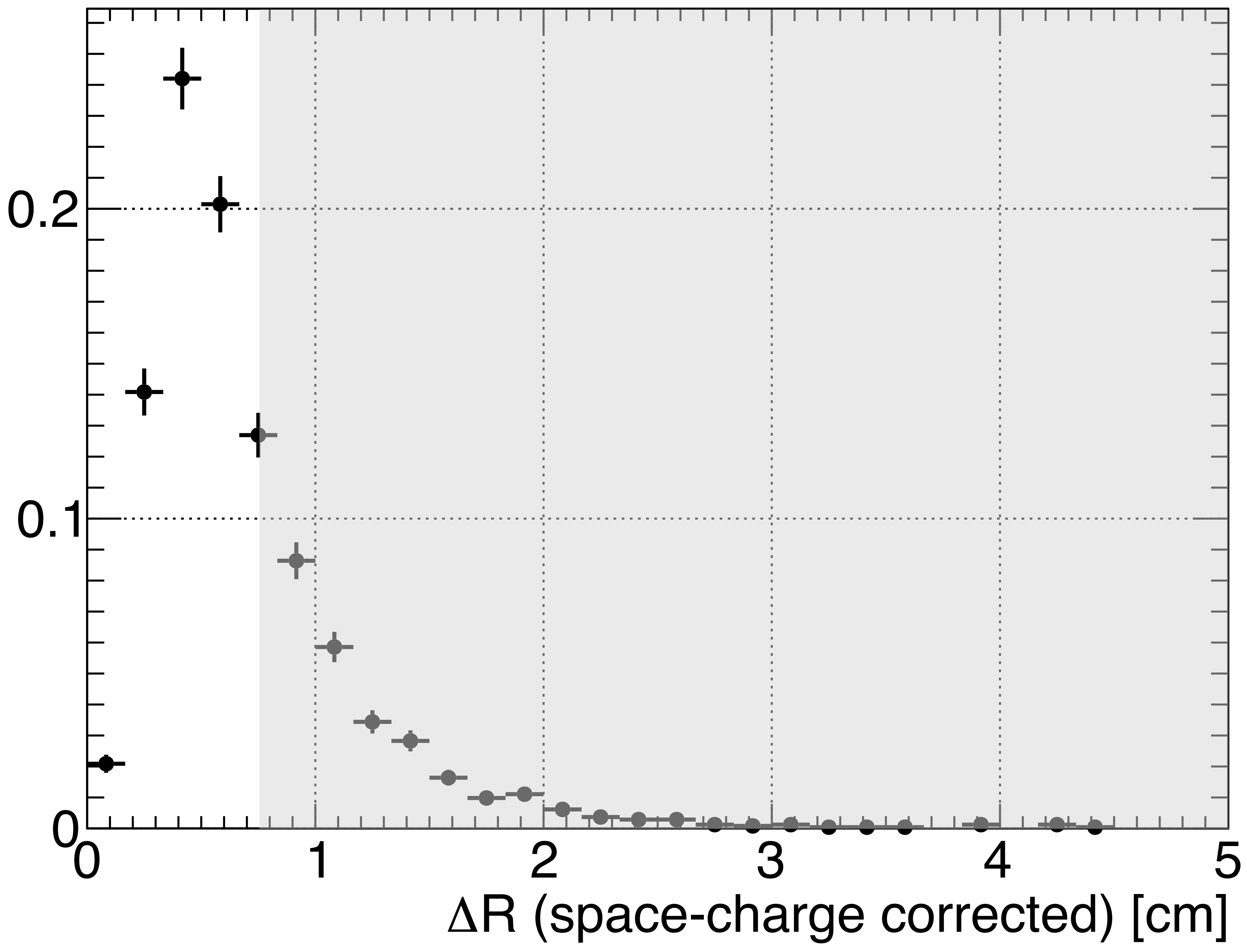




OpenCV

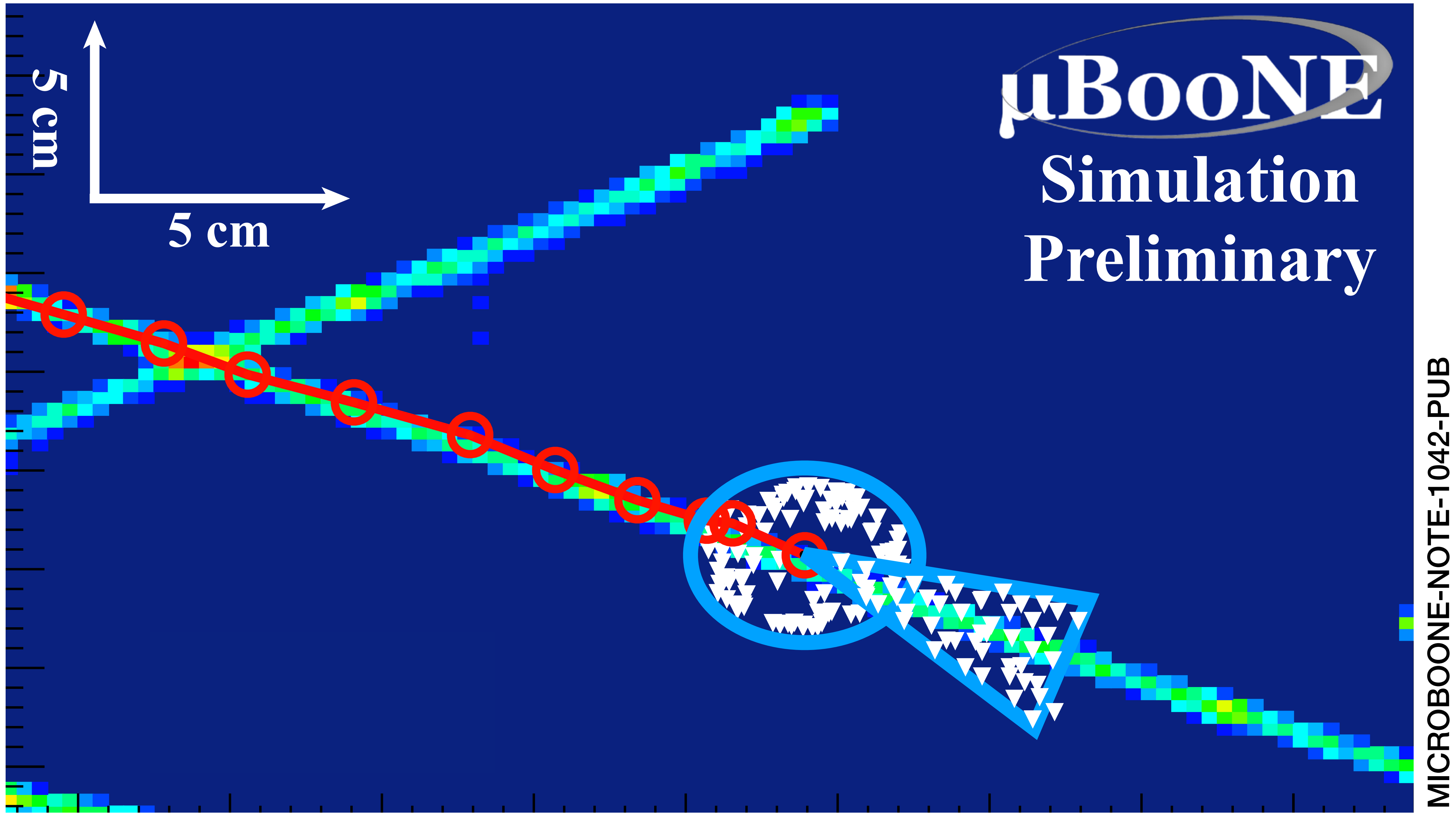
- Scan the track-only pixels around found vertex seeds
- For each location, draw a circle centered on the considered point
- Look for crossing points
- define angles θ and Φ
- Optimal seed position is achieved when θ ~ Φ

Best Vertex Location



- Seeds are then compared across images
  - temporal coincidence
  - 3D consistency
  - only 2 prongs coming out of the vertex
- Cluster pixels coming out os the reconstructed vertex point
- **Spatial resolution of the vertex finding:**
  68% of the neutrino candidates have a reconstructed vertex within **0.75 cm** of the true vertex

Track Reconstruction



Random points in 3D in:

- **Sphere around the last found point**
  - "physics independent" : no assumption on expected curvature radius, kinks, …
- **Forward cone**
  - $r_{cone} = 2.r_{sphere}$
  - $\theta_{open} = 30°$
  - average direction of last 10 cm of the track
  - Assumes a globally straight track
  - Helps jumping over dead regions and faint tracks

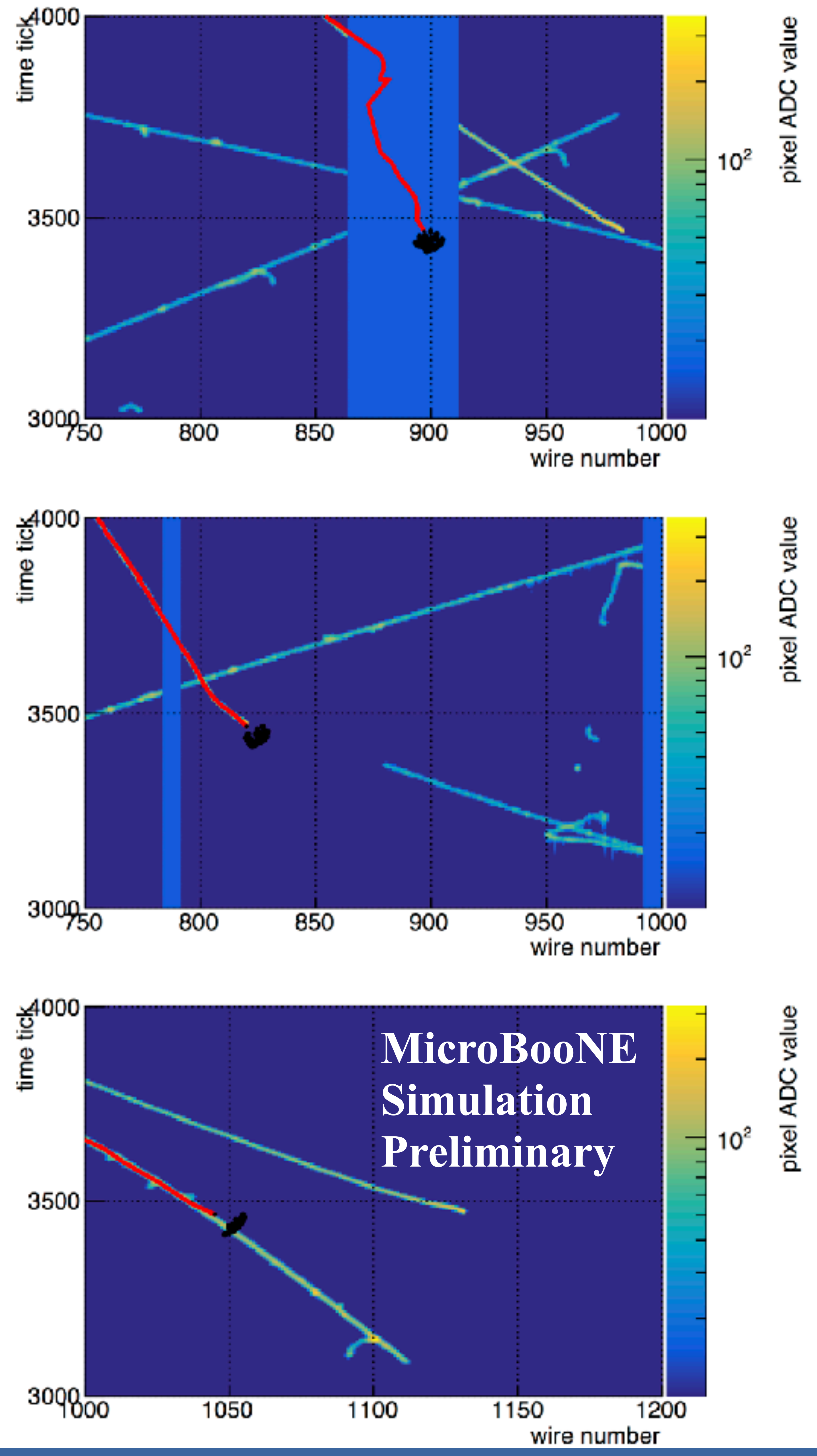
Reconstruction Example

	true	reconstructed
E_ν	= 974.8 MeV	= 993 MeV
KE_μ	= 602.9 MeV	= 626.8 MeV
KE_p	= 225.9 MeV	= 220.6 MeV

- Kinetic energy from the reconstructed range
- Proton/muon candidate based on average pixel intensity
- **Neutrino energy :** $E_\nu^{\text{range}} = \text{KE}_p^{\text{range}} + \text{KE}_\mu^{\text{range}} + m_\mu + m_p - m_n + B$
- B is an effective nuclear binding energy for the CCQE interaction (~40 MeV)

Tracking diagnostic

- At the end of each track throw 3D points in a forward spherical cap of radius 3 cm and opening angle 37°
- 3 possible cases:
  - points in dead region
  - points in empty region
  - points on a non-empty region
- All in empty pixel = reached end of track
- 2 planes in dead regions and 1 plane empty = tracker stopped in dead region
- Other cases are failing in the middle of tracks
- Attribute a "good reconstruction" label to each track found in the vertex



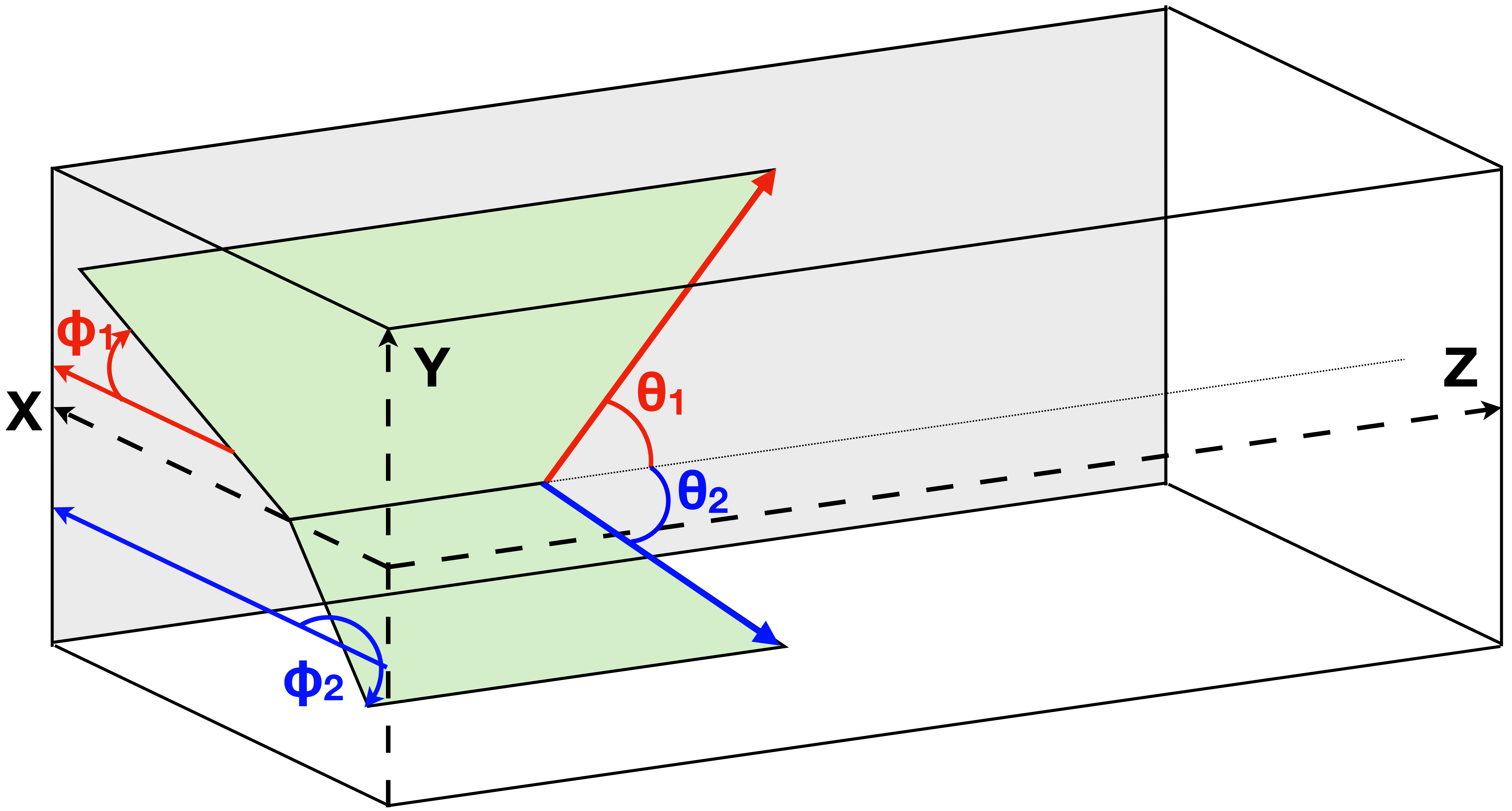
MICROBOONE-NOTE-1042-PUB

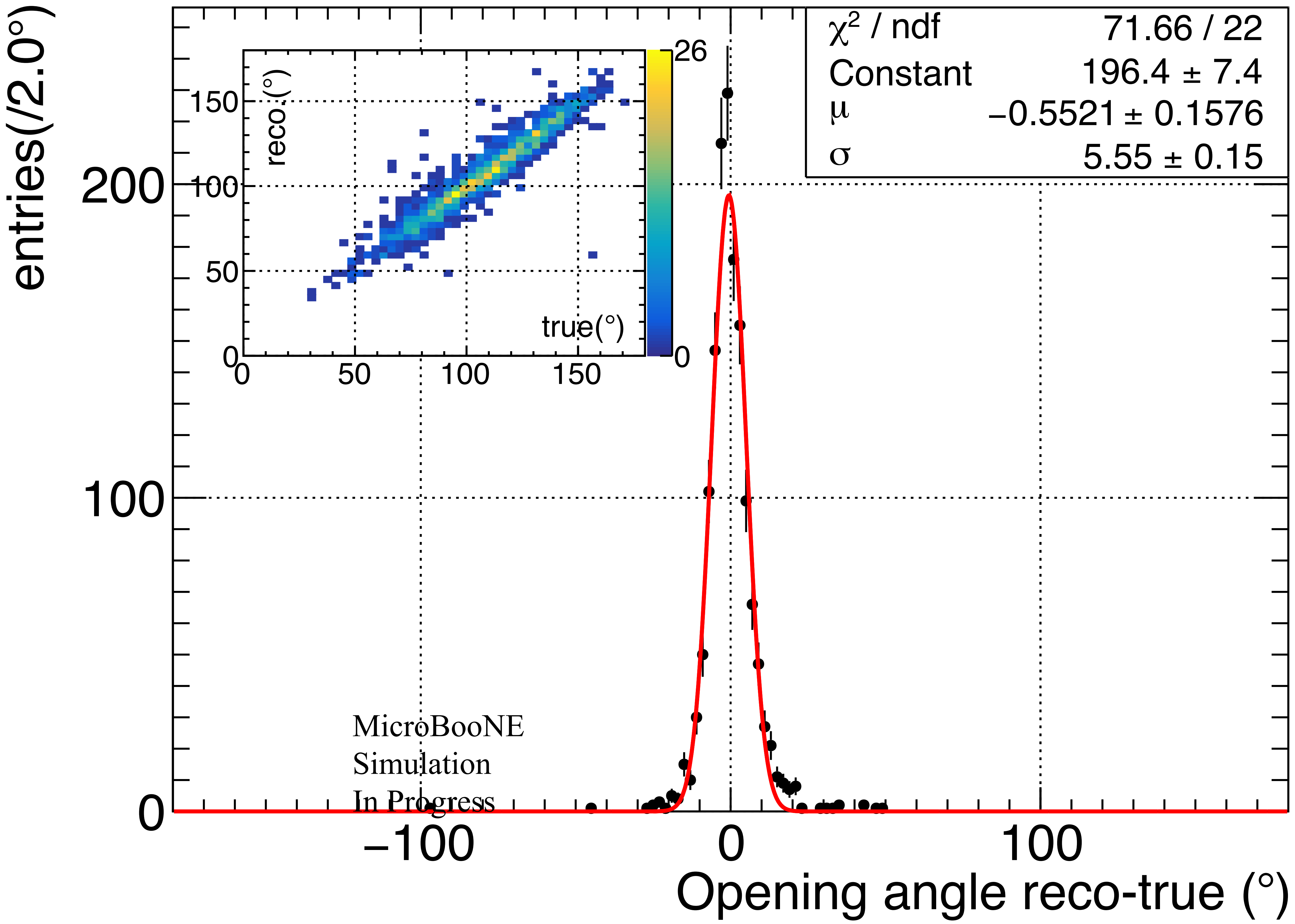
Reconstruction Example

true	**reconstructed**
E_ν = 496.5 MeV	E_ν = 498 MeV
KE_μ = 195.5 MeV	KE_μ = 201.2 MeV
KE_p = 157.1 MeV	KE_p = 162.6 MeV

- **Reach dead wires in two planes :**
  - Estimate direction before dead wires
  - Push through dead region
  - hopefully reconnect to rest of the track
- Mange to recover **~20% additional events**

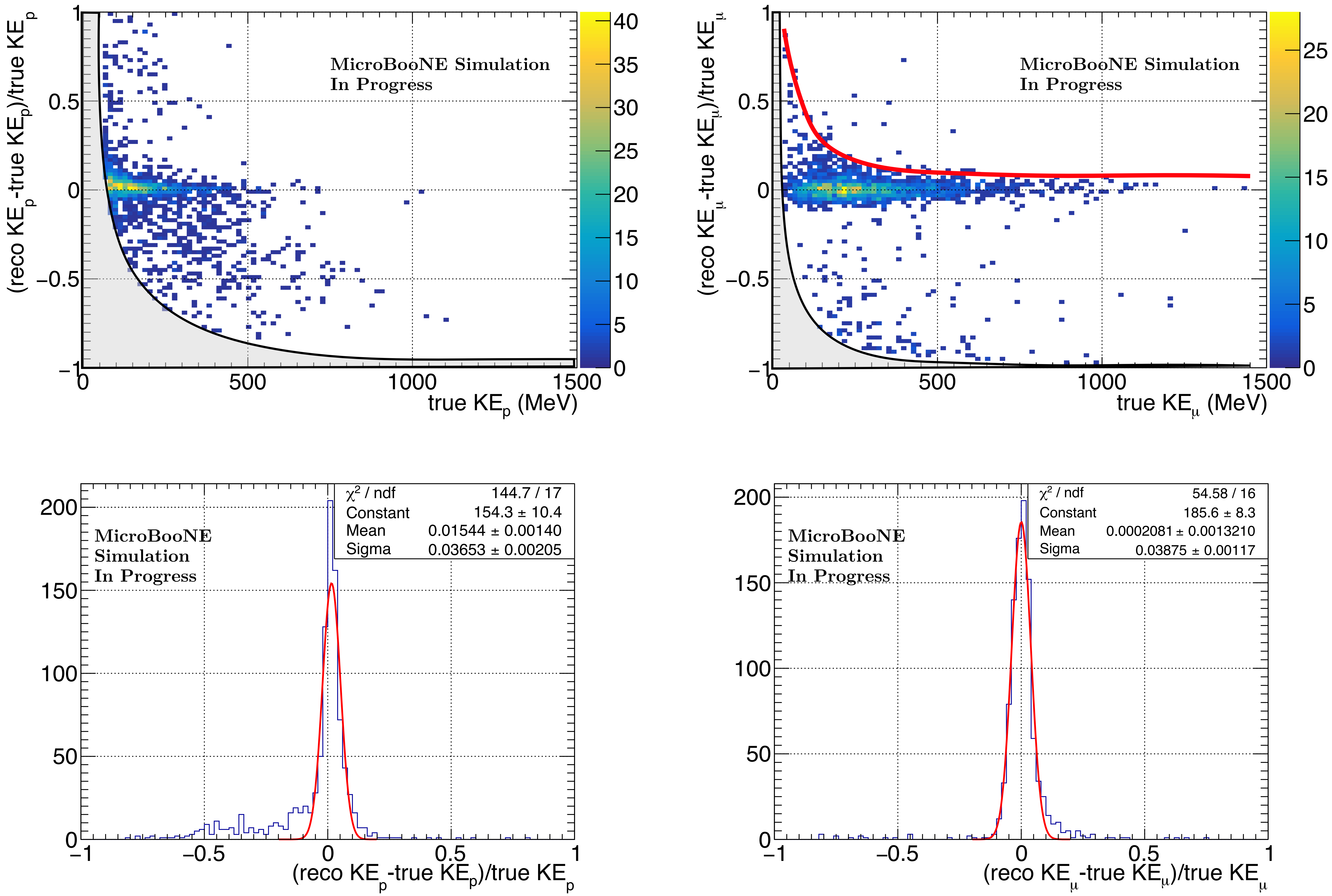
Angular Resolution





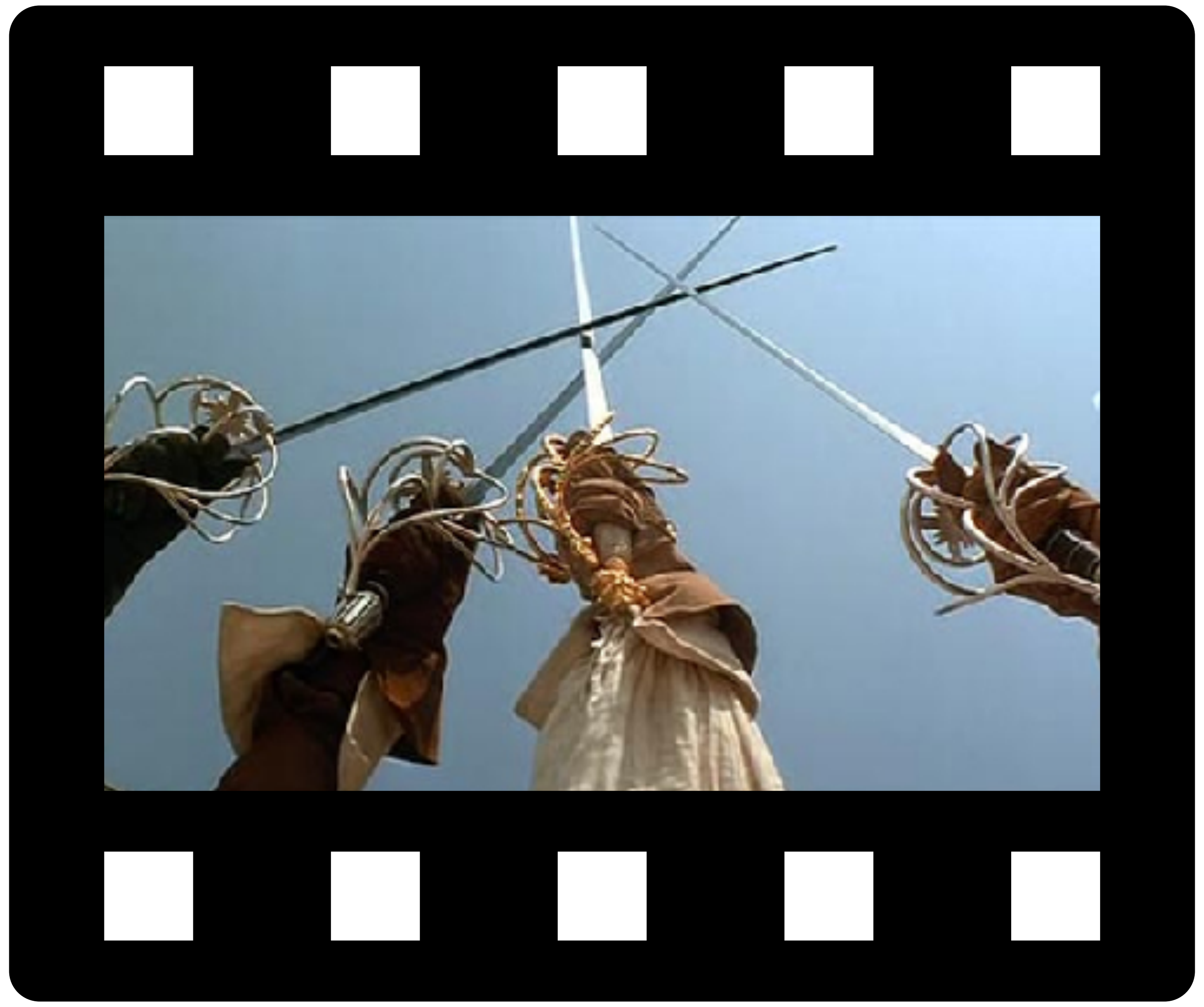
- Each track is associated to two angles:
  - θ angle with respect to the beam direction
  - Φ the angle of the projection in the (X,Y) plane with respect to the X axis
- Define the opening angle as the angle between two tracks

Track Reconstruction performances



- Kinetic energy estimated on the range of the reconstructed tracks
- Residual error show no systematic bias with respect to true kinetic energy
- About 4% energy resolution on each individual particle

3 energy definitions



$$E_\nu^{\text{range}} = \text{KE}_p + \text{KE}_\mu + M_\mu + M_p - (M_n - B)$$

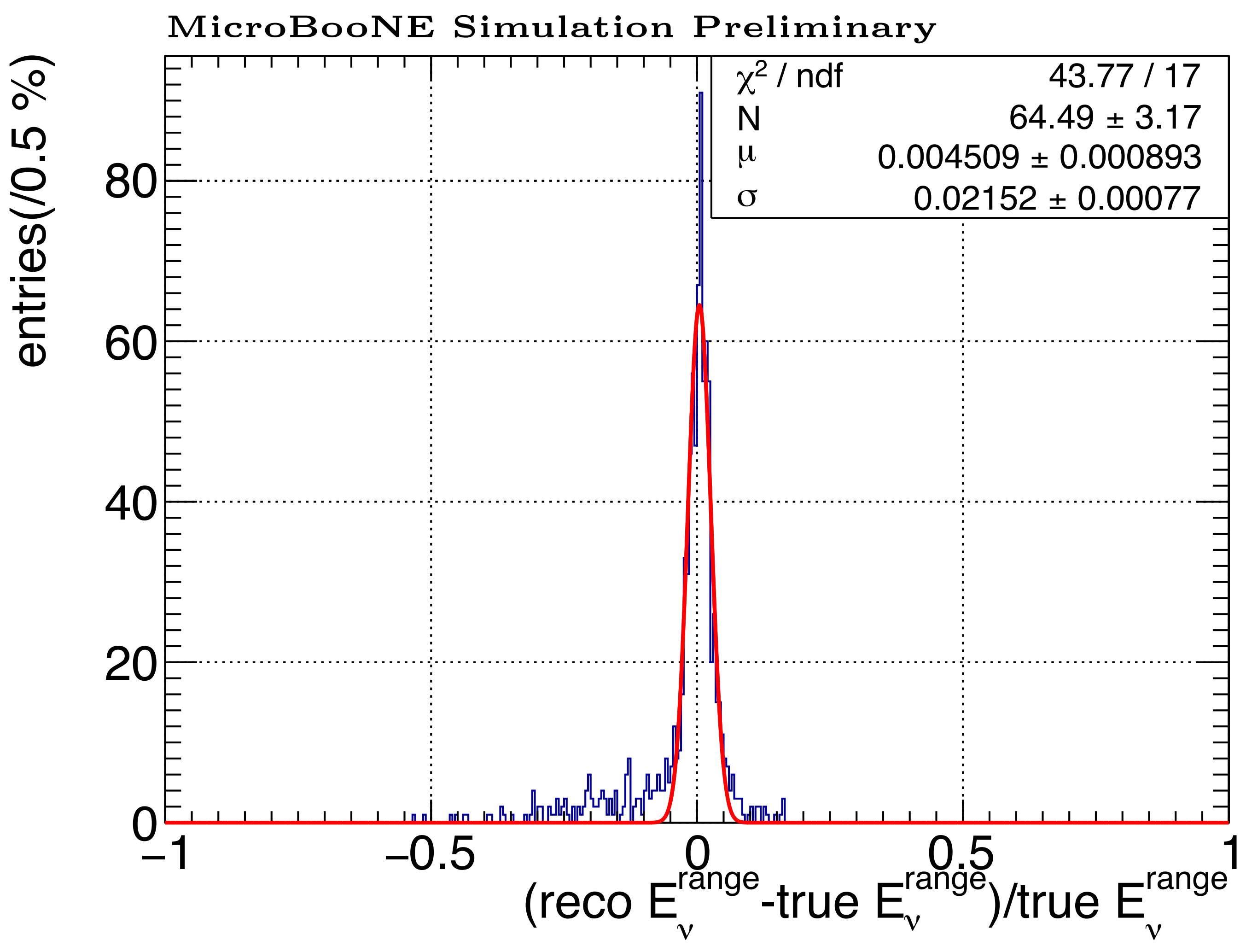
$$E_\nu^{QE}[p] = 0.5 \cdot \frac{2 \cdot (M_n - B) \cdot E_p - ((Mn - B)^2 + M_p^2 - M_\mu^2)}{(M_n - B) - E_p + \sqrt{(E_p^2 - M_p^2)} \cdot \cos\theta_p}$$

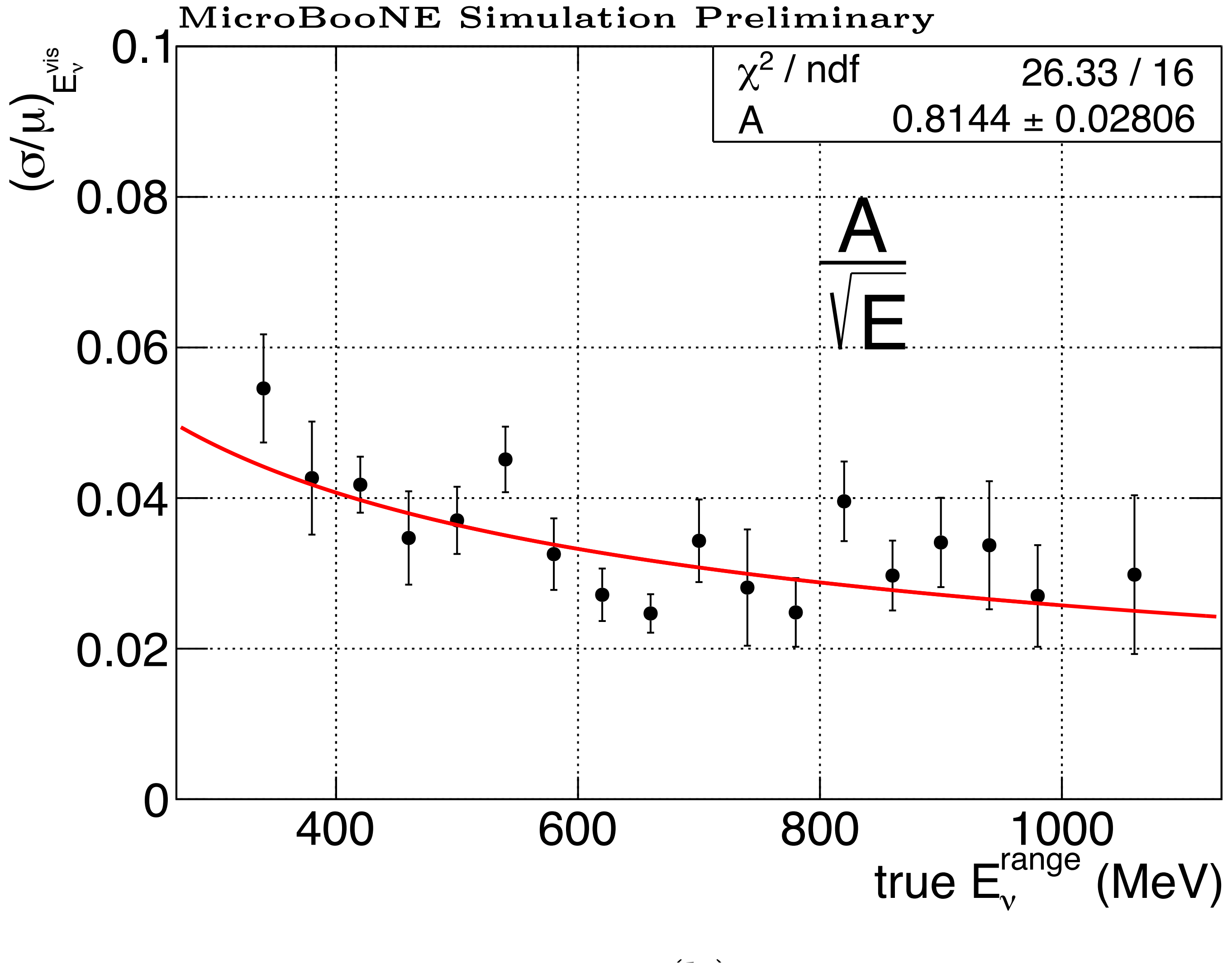
$$E_\nu^{QE}[\mu] = 0.5 \cdot \frac{2 \cdot (M_n - B) \cdot E_\mu - ((Mn - B)^2 + M_\mu^2 - M_p^2)}{(M_n - B) - E_\mu + \sqrt{(E_\mu^2 - M_\mu^2)} \cdot \cos\theta_\mu}$$

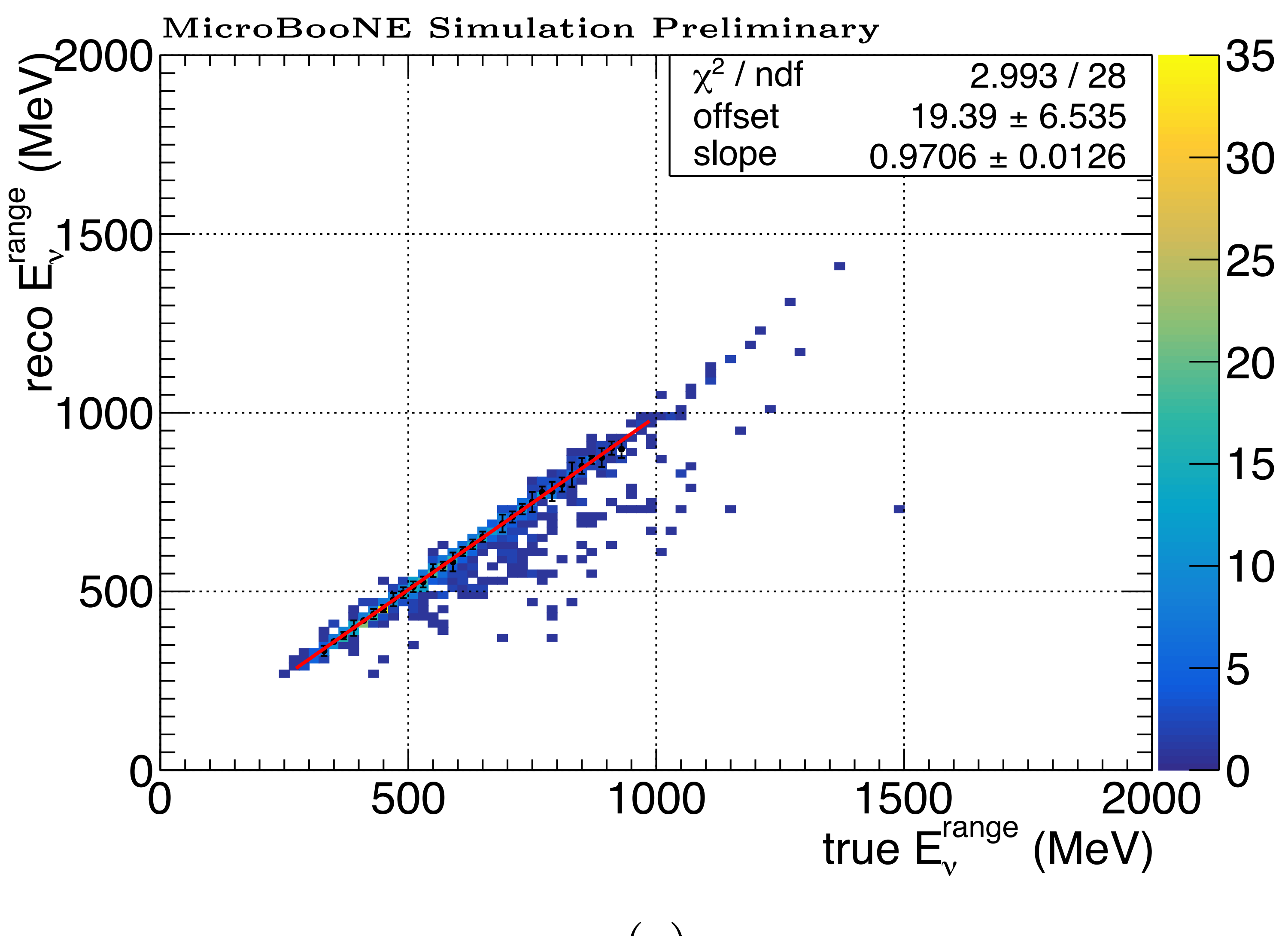
- Access to the **full kinematics of the muon and the protons**
- Assuming **1μ1p CCQE** interaction, we can access the neutrino energy
- MiniBooNE used only the muon kinematics to estimate the neutrino energy
- All three energies should (roughly) agree for 1l1p CCQE events,
  but not for more complex topologies, or cosmic background

- The same can be done with an electron hypothesis in the ν_e case

Track Reconstruction Performance





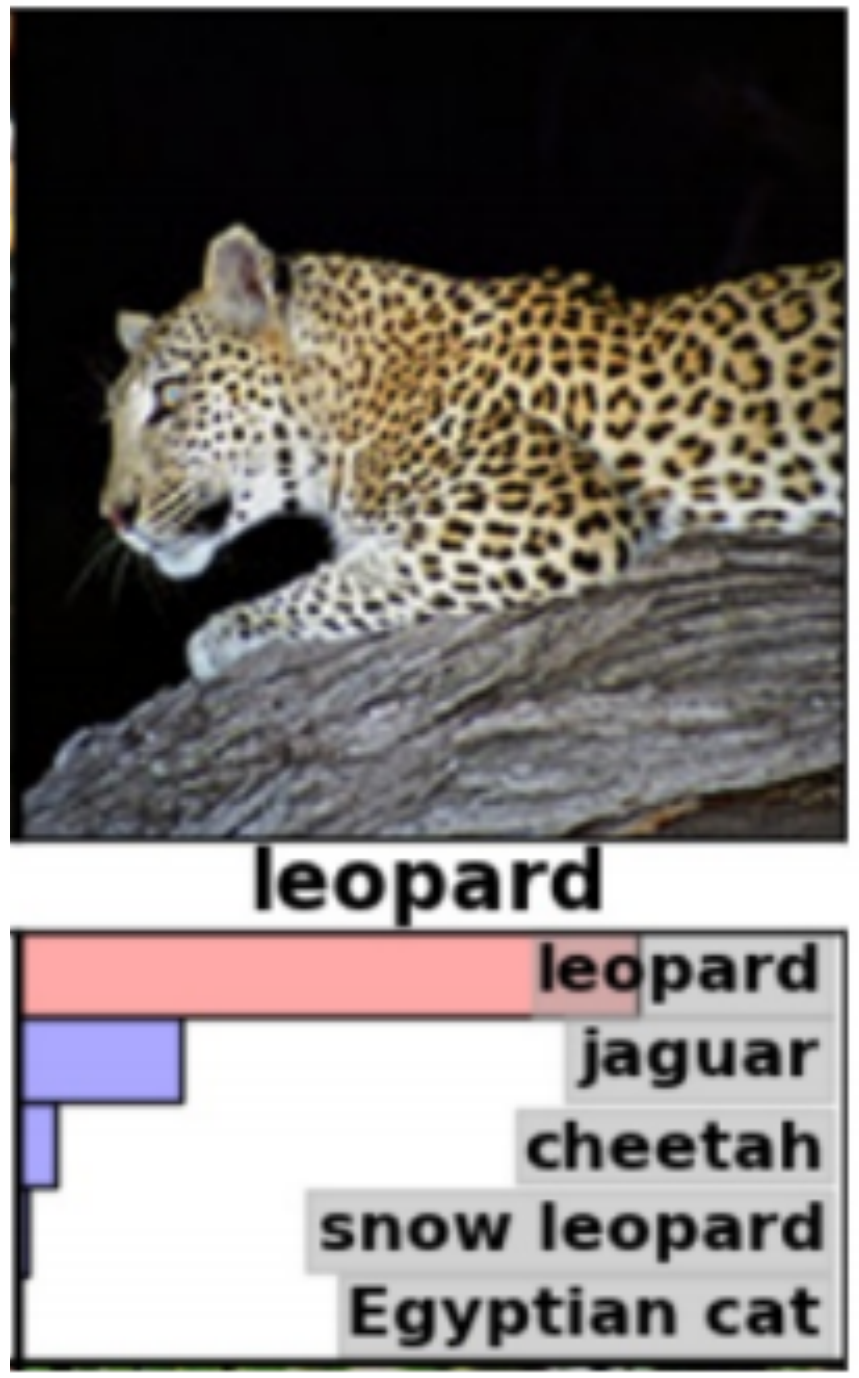


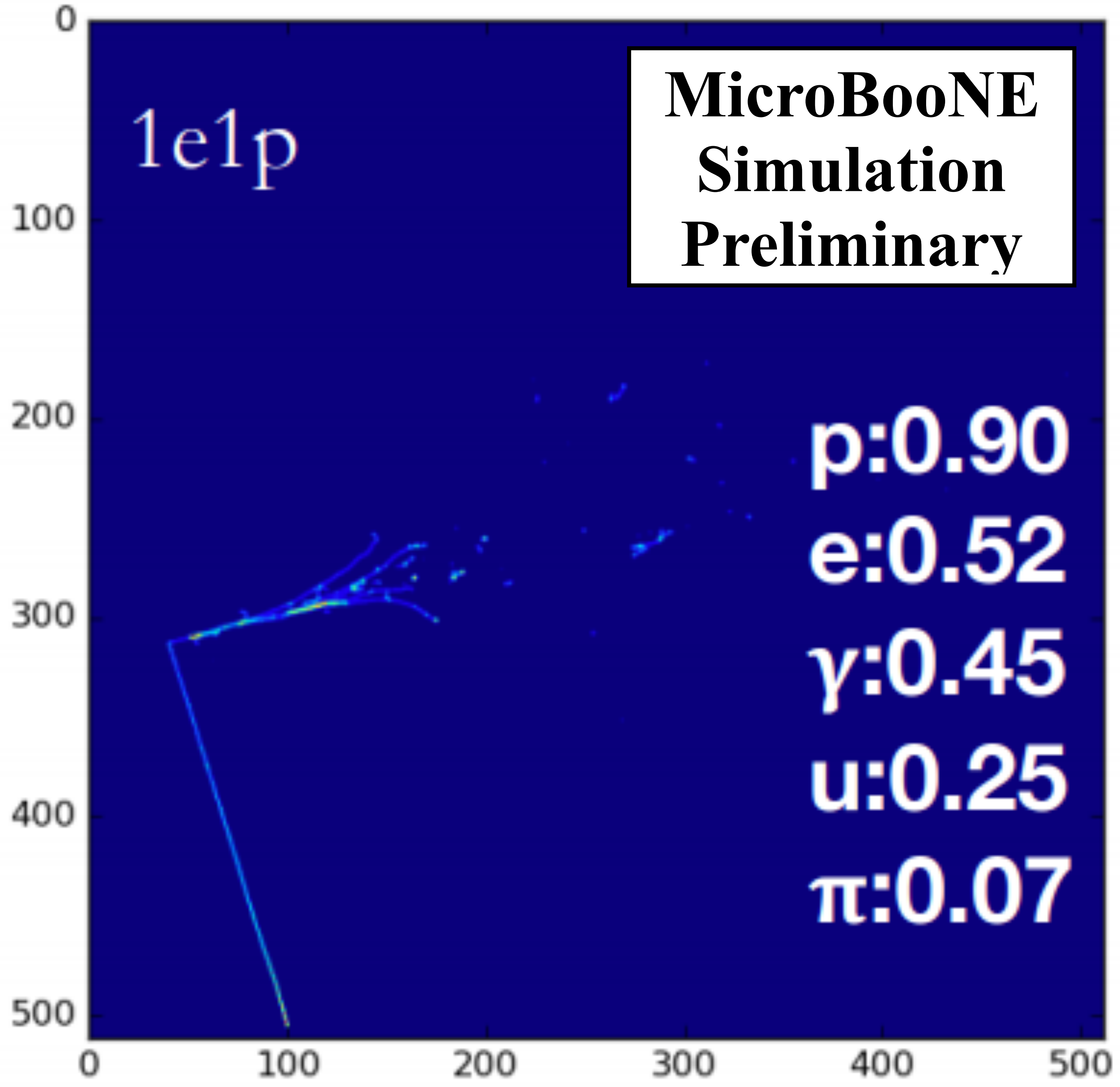
MICROBOONE-NOTE-1042-PUB

- Estimate the resolution for:
  - contained 1μ1p νμ interactions,
  - true muon kinetic energy > 35 MeV,
  - true proton kinetic energy > 60 MeV
- **Overall energy range : (2.2±0.1)%**
- Evolution in $1/\sqrt{E}$ typically dominated by stochasticity
  - $81\%/\sqrt{E}$(MeV) = $2.5\%/\sqrt{E}$(GeV) => **meets DUNE resolution target**

Particle ID

- Use a categorization CNN to identify contents of the image centered around the reconstructed tracks
- Classify the probability of presence of 5 types of particles : p,μ,π,e and γ





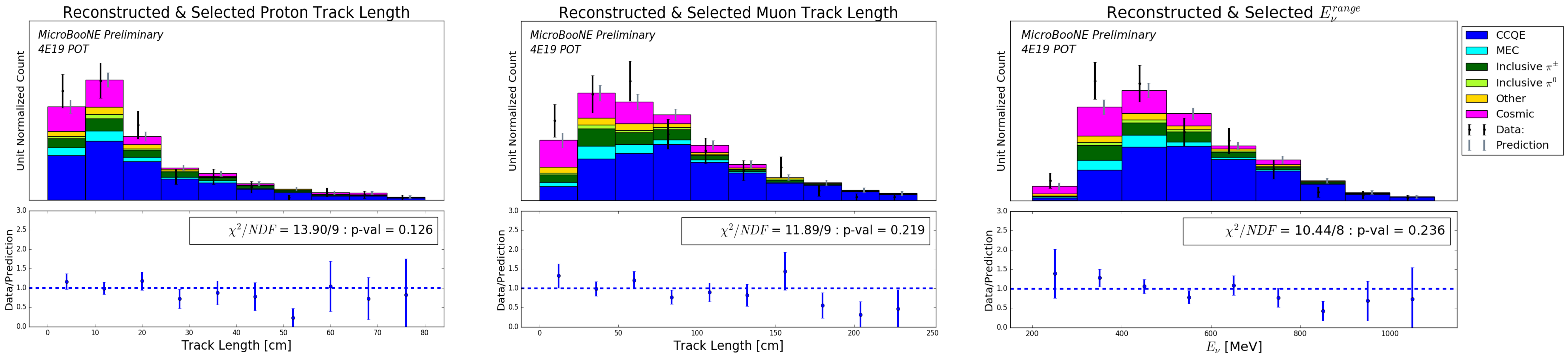
"Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber" JINST 12, P03011 (2017)

Data/Simulation Comparison

- We developed a chain of reconstruction and selection of neutrinos based on MC studies
- Need to ensure their performance on data
  - Respect blindness : small data sample of ~$4x10^{19}$ POT
  - Off-beam sample for cosmic rays studies
  - MC sample of beam neutrino interactions
- Simulated beam neutrino interactions and cosmic sample are normalized to $4x10^{19}$ POT and for a predicted spectrum to be compared to data
- Look for significant shape-only differences

Data/Simulation Comparison

MICROBOONE-NOTE-1051-PUB

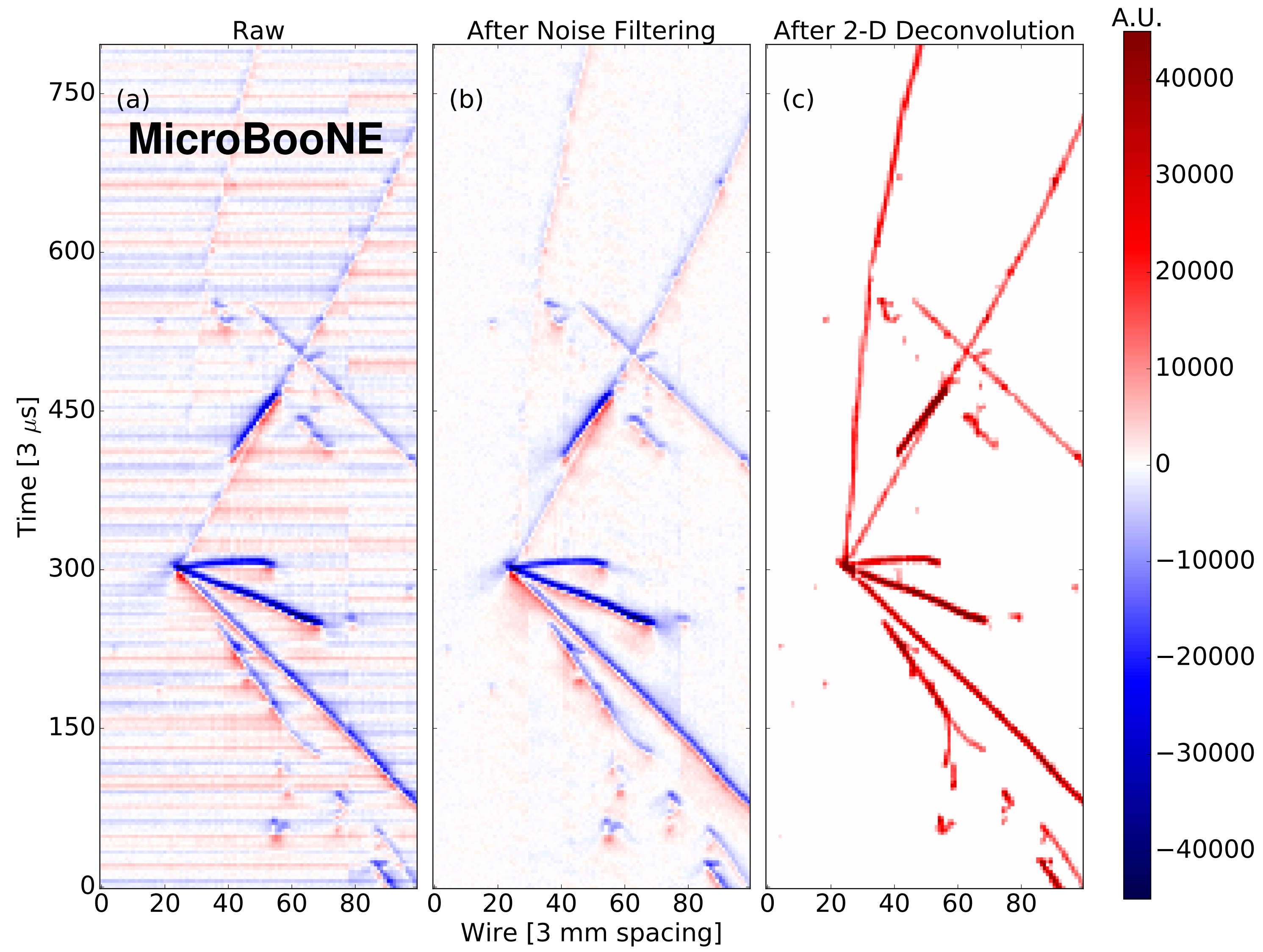


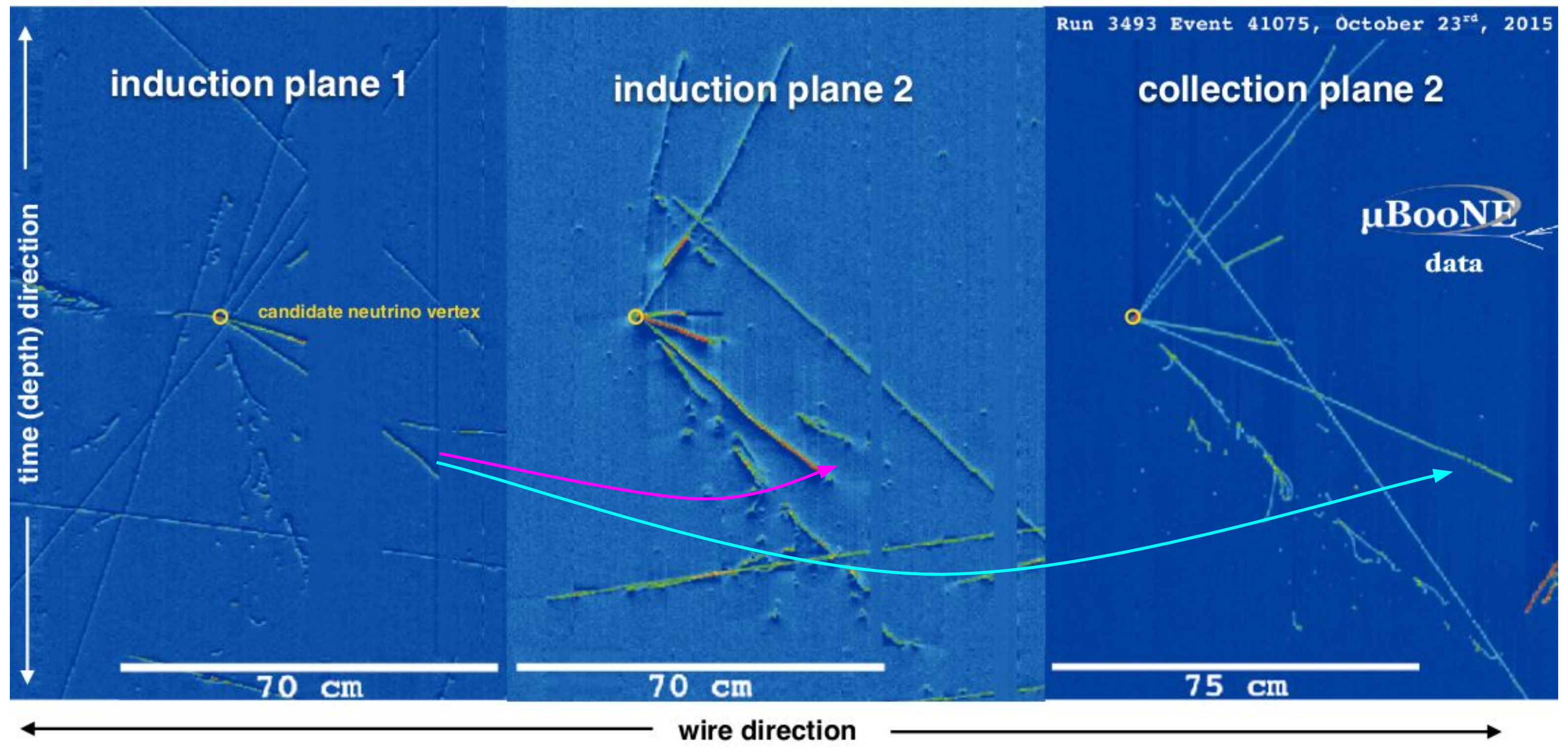
- No significant distortion in data compared to predictions (within our statistically limited sample)
- Reconstruction, identification and selection seem to behave similarly on data and Monte Carlo

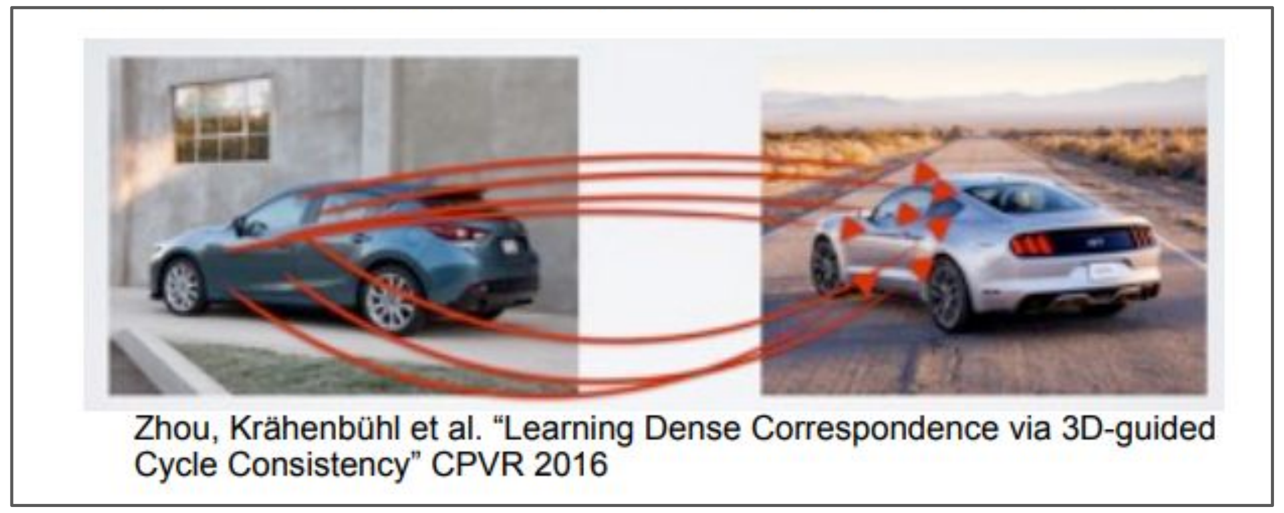
Systematic Uncertainties

- **Currently available :**
  - Beam flux uncertainties
  - ν-Ar uncertainties
  - Oscillation fit and sensitivity study machinery taking into account full systematics
- **In progress : detector-based systematics:**
  - One simulated beam neutrino sample
  - Vary detector parameters in multiple possible "universes"
  - Build correlations and covariance matrices from the universes

Coming soon







- 2D deconvolution : tracks clearer, easy to follow
- Wire-to-wire cross-talk better accounted for

- Work on a new SSNet that learns spatial coherence
- Knows about rotations between the planes

- Work on a new CNN to fill in gaps in images
- No more dead wires!

Conclusions

- MicroBooNE employs a **novel technology** to investigate MiniBooNE's low energy excess
- **Several analyses in parallel**, developing **independent tools** that can be valuable for later LArTPC programs
- Data/prediction only show minor disagreement (not statistically significant), shows **good maturity of the chain**
- Upcoming **improved signal processing and neutrino generators** will improve reliability of the predictions and robustness of the Monte Carlo events


Thank you!