Lessons learned from ArgoNeuT*

*What MicroBooNE can learn/inherit from ArgoNeuT data analysis?

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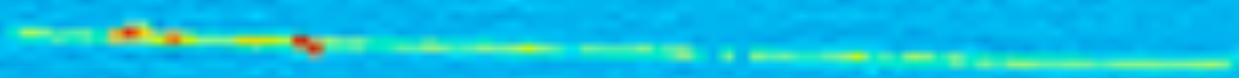
Oscillation group meeting - MicroBooNE

July 22nd 2013 - FNAL

TALK "ARGONEUT ANALYSIS STATUS" AT THE MAY 2013 MICROBOONE COLL MEETING

- ✓ $\nu_\mu/\bar{\nu}_\mu$ **CC** INCLUSIVE ANALYSIS
- ✓ "TOPOLOGICAL" ANALYSIS APPROACH
- ✓ IMPACT OF NUCLEAR EFFECTS. HINTS FROM ARGONEUT DATA
- ✓ NEUTRINO ENERGY RECONSTRUCTION



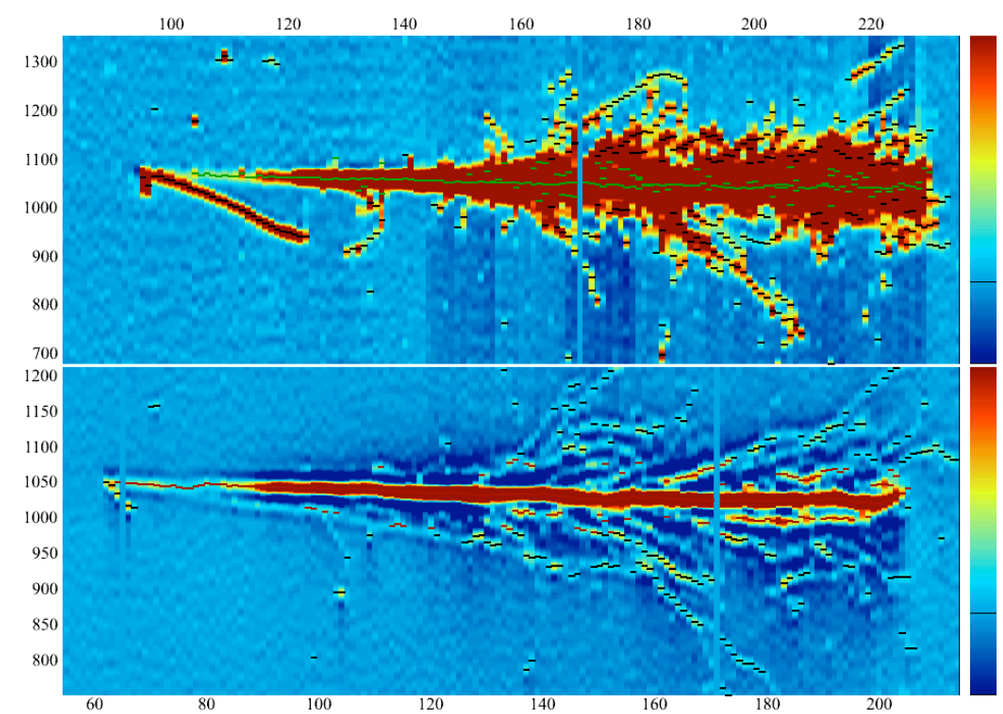
- ✓ ELECTRON-γ SEPARATION
- ✓ NEUTRAL CURRENT π^0
- ✓ CCQE HYPERON PRODUCTION
- ✓ ELECTRON RECOMBINATION

TODAY'S OUTLINE

Example: exclusive measurement of events with 1 e.m. shower+protons and neutrons

RECONSTRUCTION

- Vertex reconstruction+clustering
- Calorimetric reconstruction
  - Electronic Calibration factor
  - Recombination effect
- Neutrino energy reconstruction
- Neutron reconstruction
  - MC based correction for n->p



- DATA-MC comparison

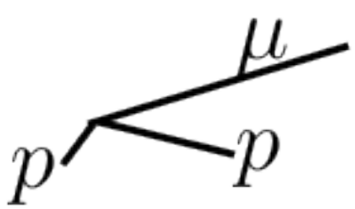
Focus on problems more than on results!

ν_μ CC EVENT TOPOLOGY

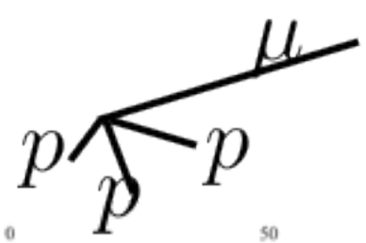
A leading muon (mip) track and one (or more) short heavily ionizing track(s) at the vertex

$1\mu + 0p$

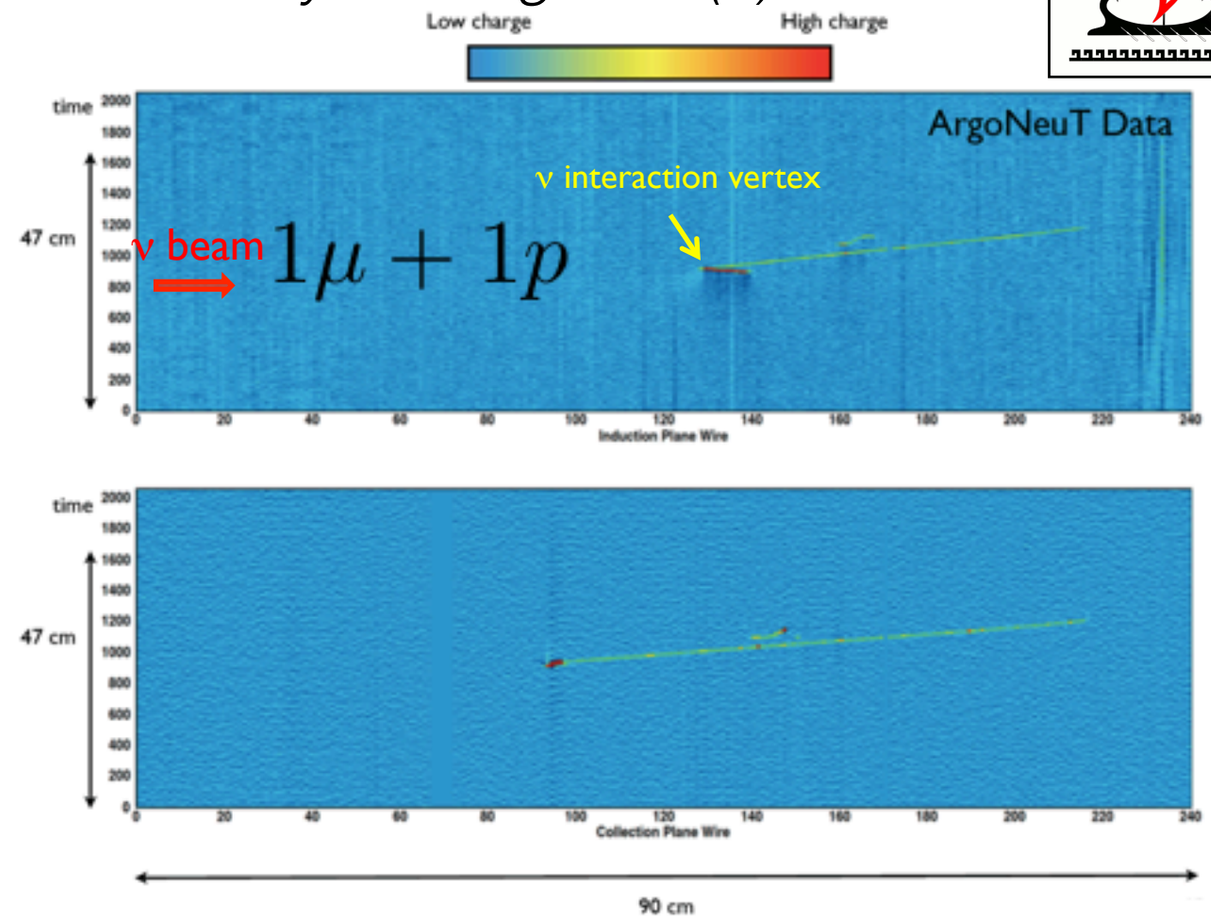
$1\mu + 1p$

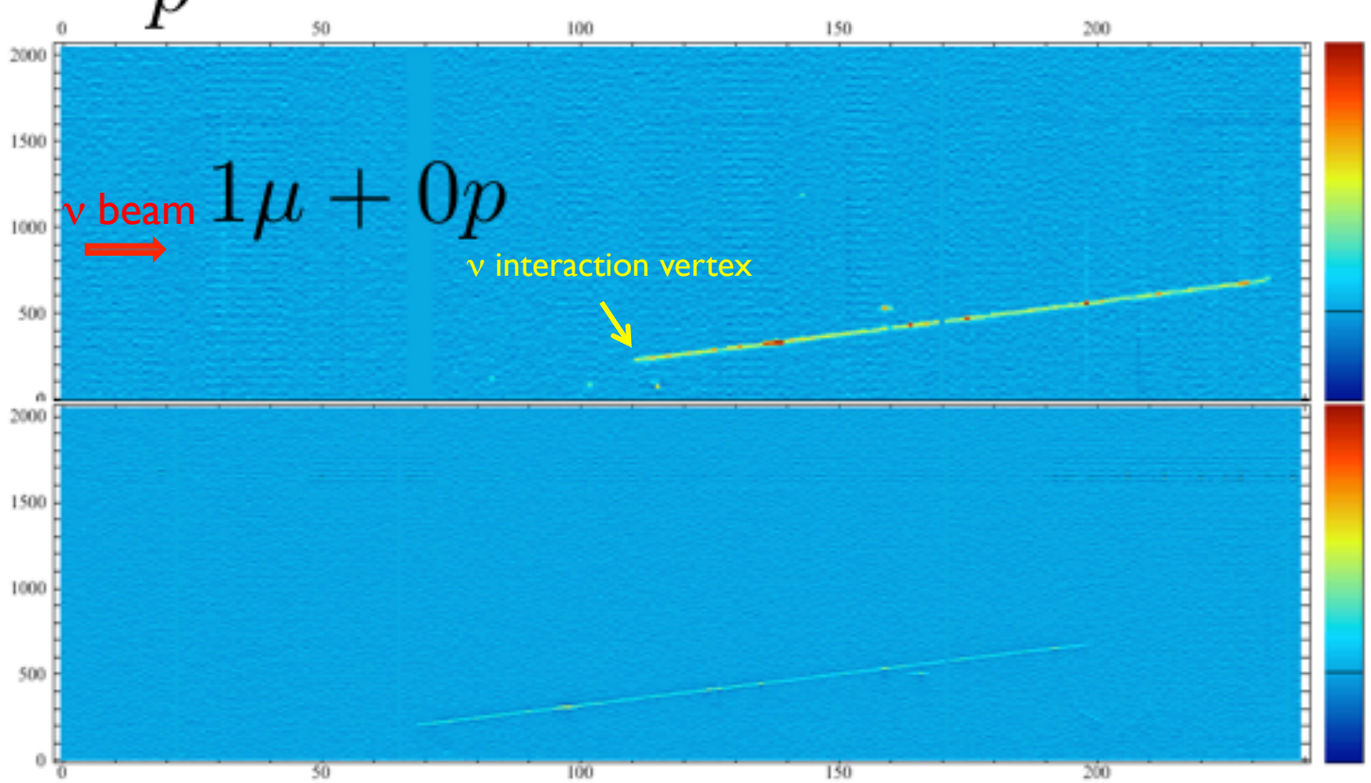


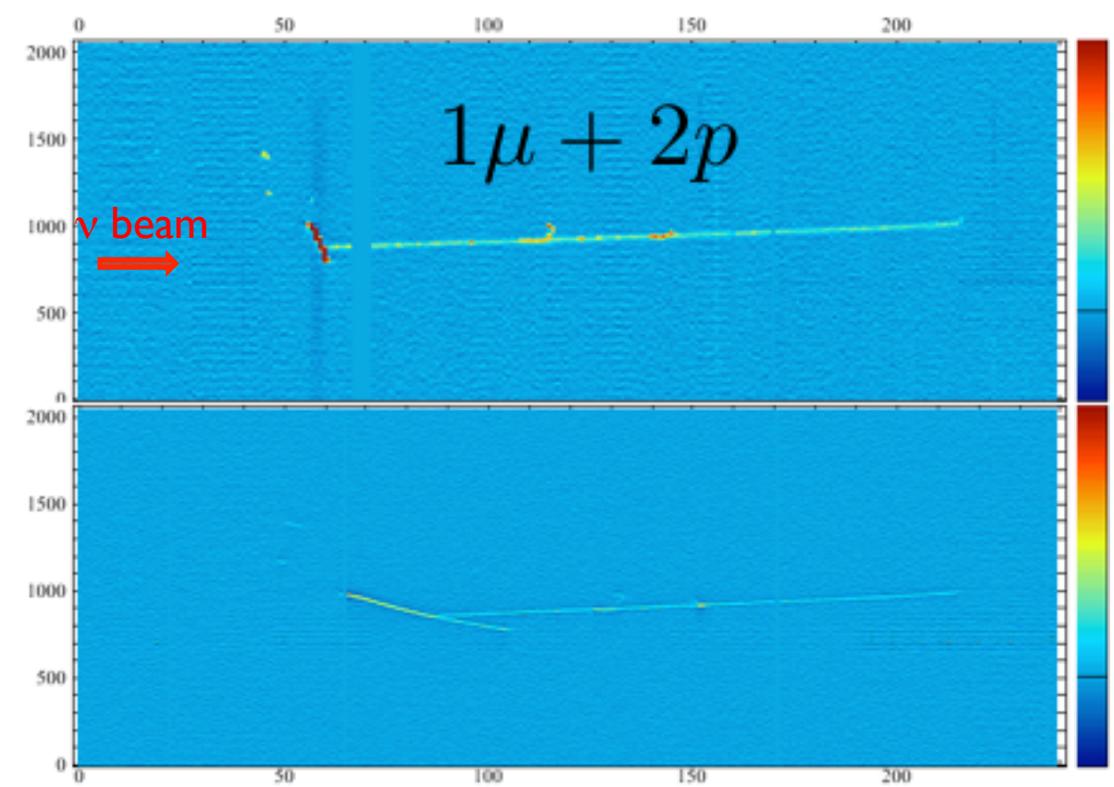
$1\mu + 2p$



$1\mu + 3p$





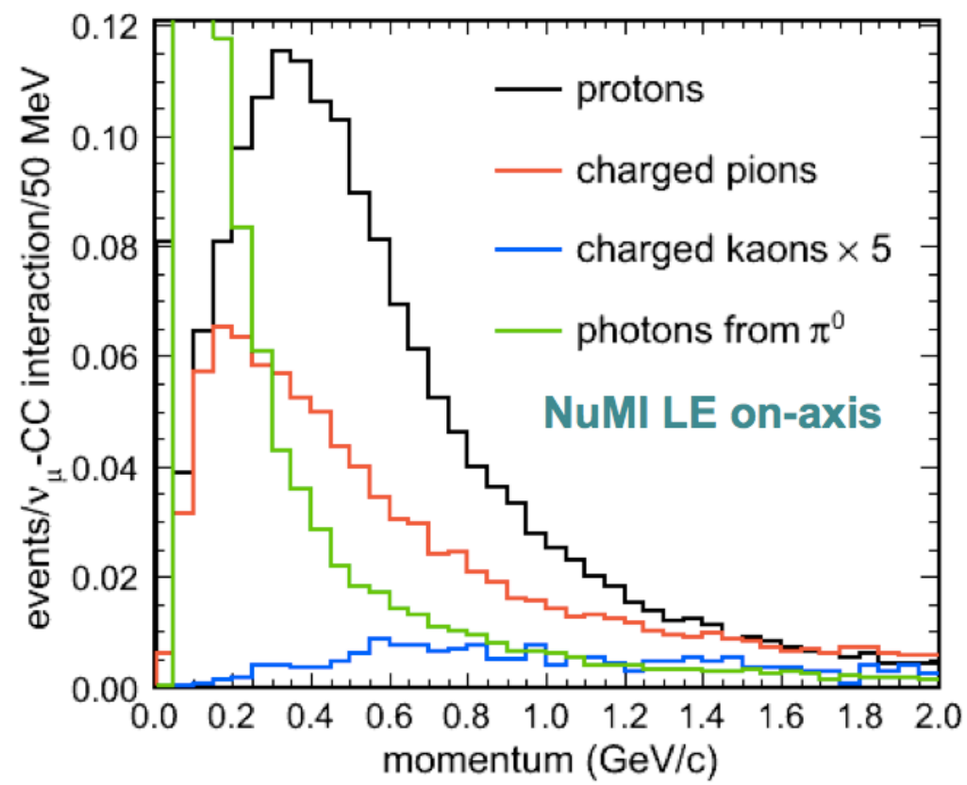


LAr TPC ANALYSIS APPROACH

Count (PId) and reconstruct protons at the neutrino interaction vertex: analysis fully exploiting LAr TPC's capabilities (ex. all muon+Np events in other neutrino detectors are ν_μ "CCQE like" events)

Event reconstruction in LArTPC

- 3D and calorimetric reconstruction fc efficient Particle Identification
- Excellent resolution for final state
- Capability of "seeing" recoil proton(s
- Good p / $\pi^{\pm}$ identification capability



Particles from ν interactions

DATA ANALYSIS

- Analysis steps:
  - ✓ automated reconstruction (muon angle and momentum)
  - ✓ visual scanning } proton(s) angle and momentum reconstruction
  - ✓ calorimetric reconstruction
- Background estimate included
- GENIE MC:
  - ✓ estimate efficiency of the automated reconstruction, detector acceptance and proton containment (for PId)
  - ✓ estimate backgrounds
    - NC background
    - WS background
    - π^0 with both γ not converting

ARGONEUT ANALYSIS TOOLS

Full reconstruction software

LArSoft reconstruction
[3D + calorimetric]
+
χ^2 based PID for contained track
(new tool, recently added to LArSoft)
+
Visual scanning *(for exclusive topologies analyses)*
+
Semi-automatic reconstruction of selected events
+
EVD analysis tool

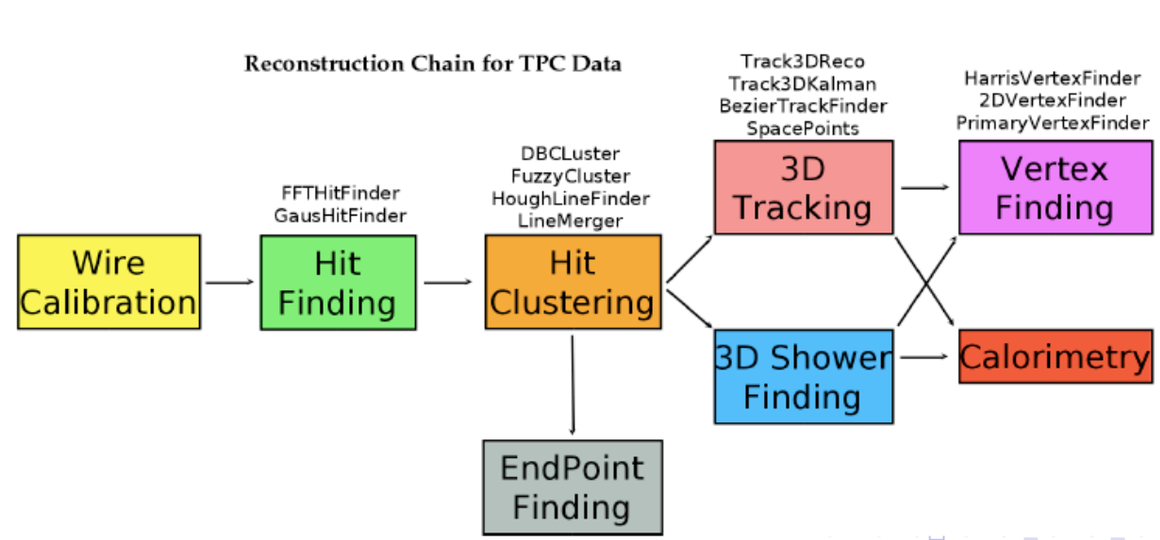
Data-MC comparison (different neutrino event generators
- including FSI but not yet including multinucleon)

ArgoNeuT 0 pion analysis

- Raw waveform treatment
- Hit identification
- 2-dimensional clustering
- 2-dimensional line reconstruction
- Vertex finding
- 2-dimensional, more refined clustering of short vertex tracks
- 3-dimensional track reconstruction
- Calorimetric reconstruction
- Matching 3-dimensional tracks with MINOS Near Detector

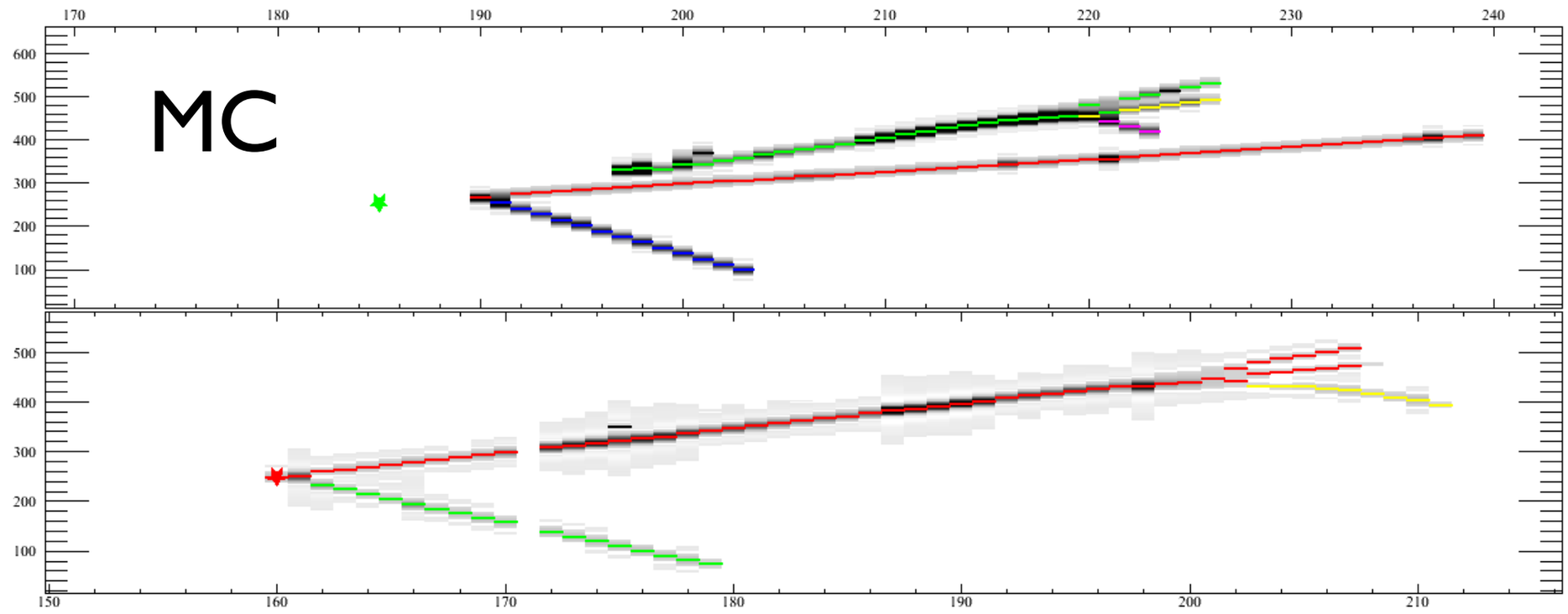
LArSOFT structure

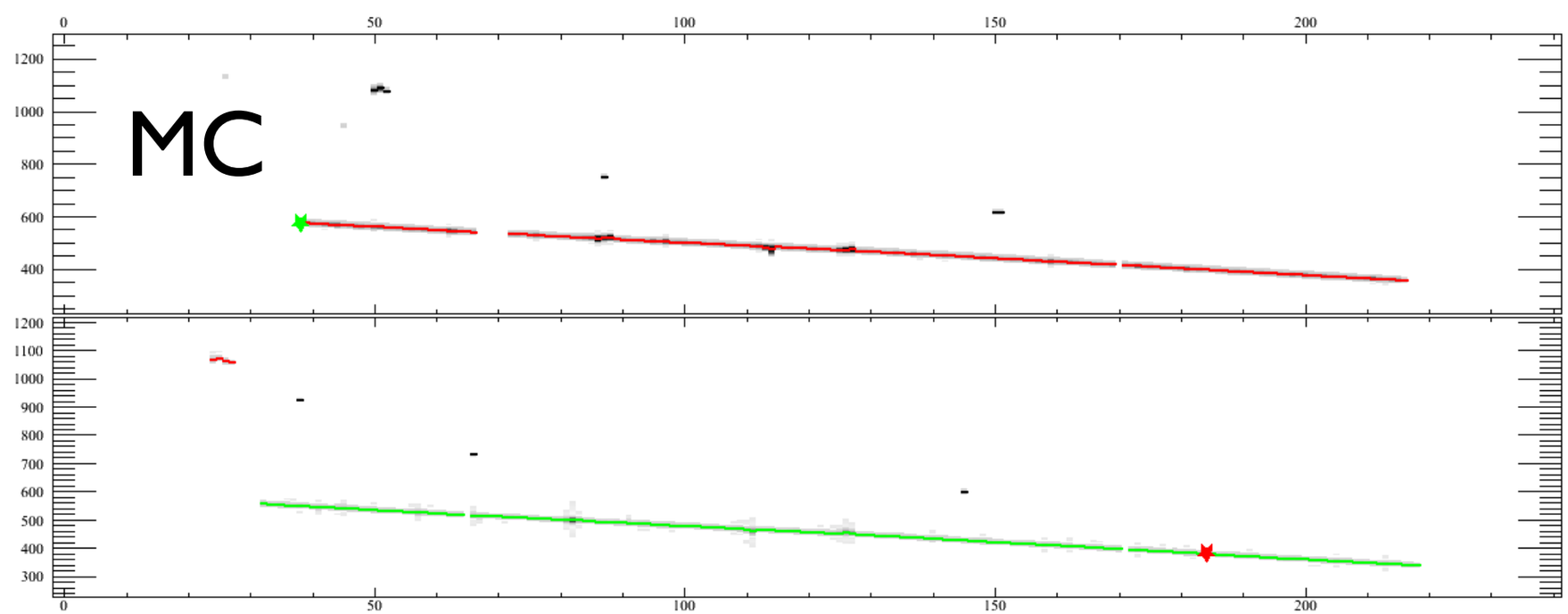
- LArSOFT is a software package developed for LArTPCs
- Detector agnostic
- Constructed from separate modules - highly configurable



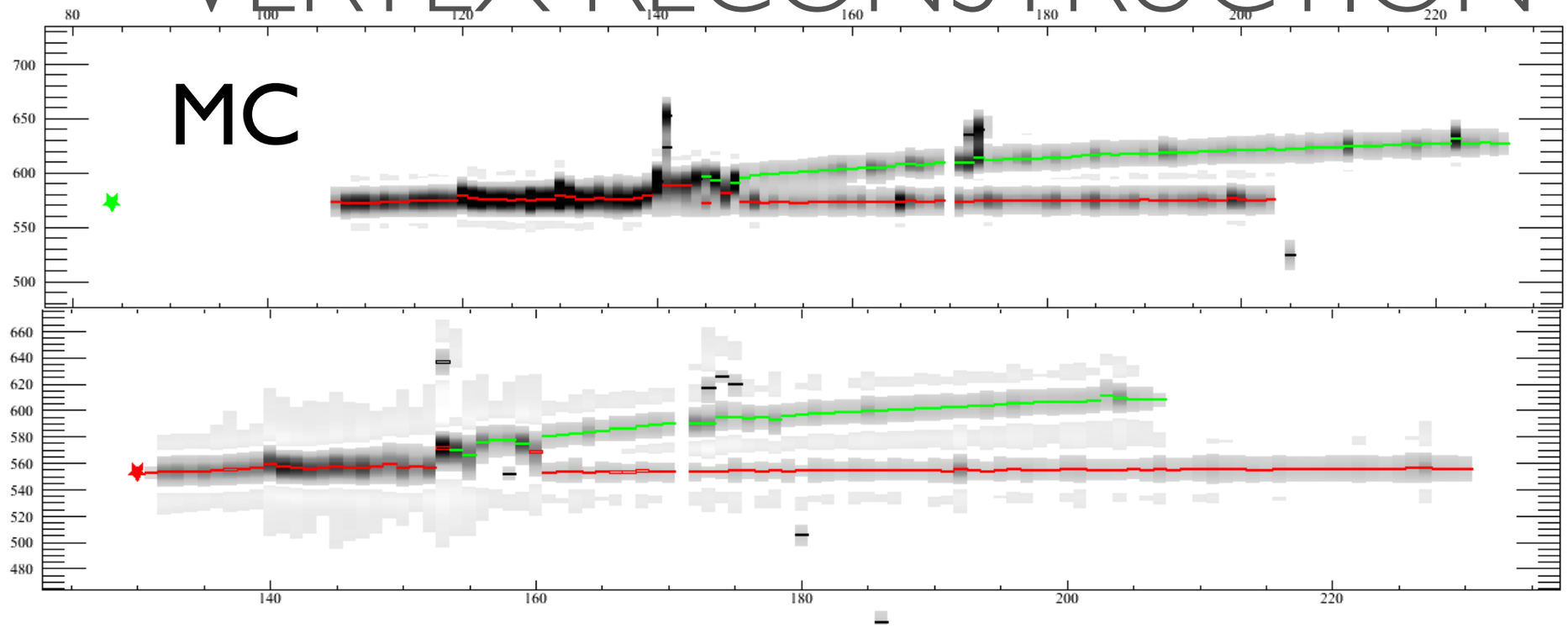
VERTEX RECONSTRUCTION

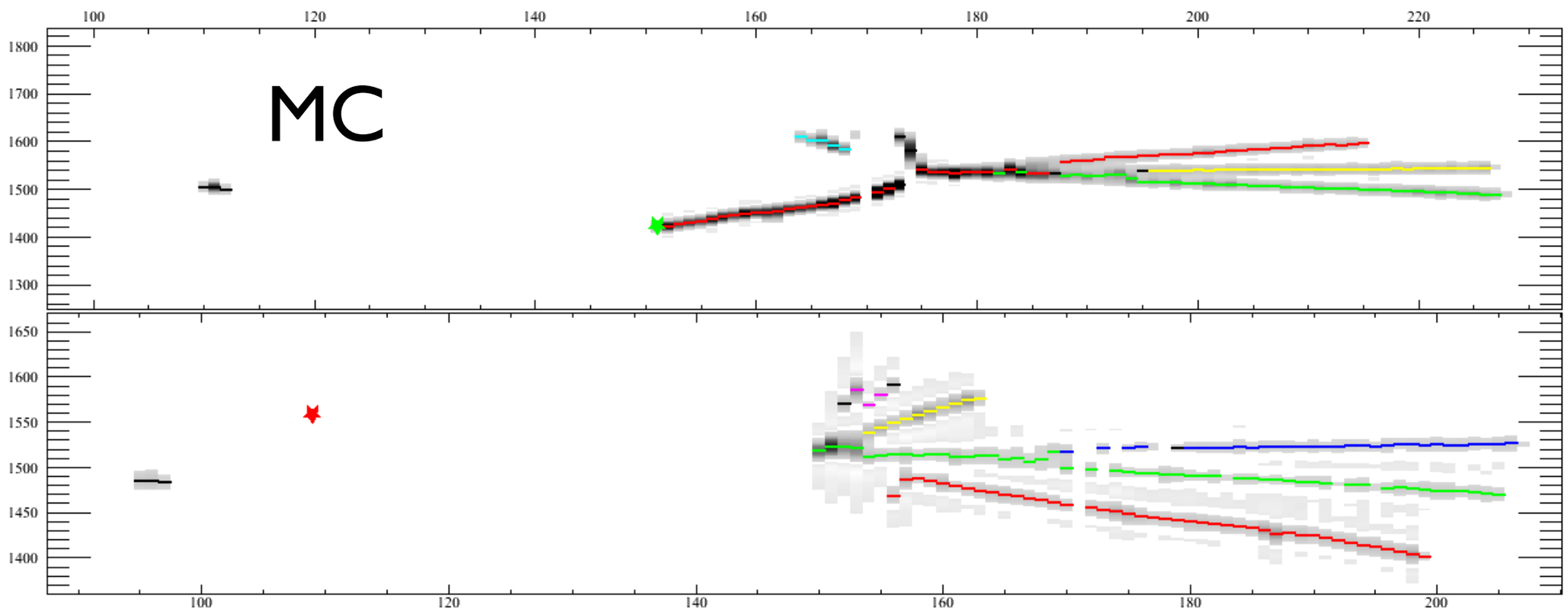
ClusterFinder2D to reconstruct vertex and displaying LineMerger clusters



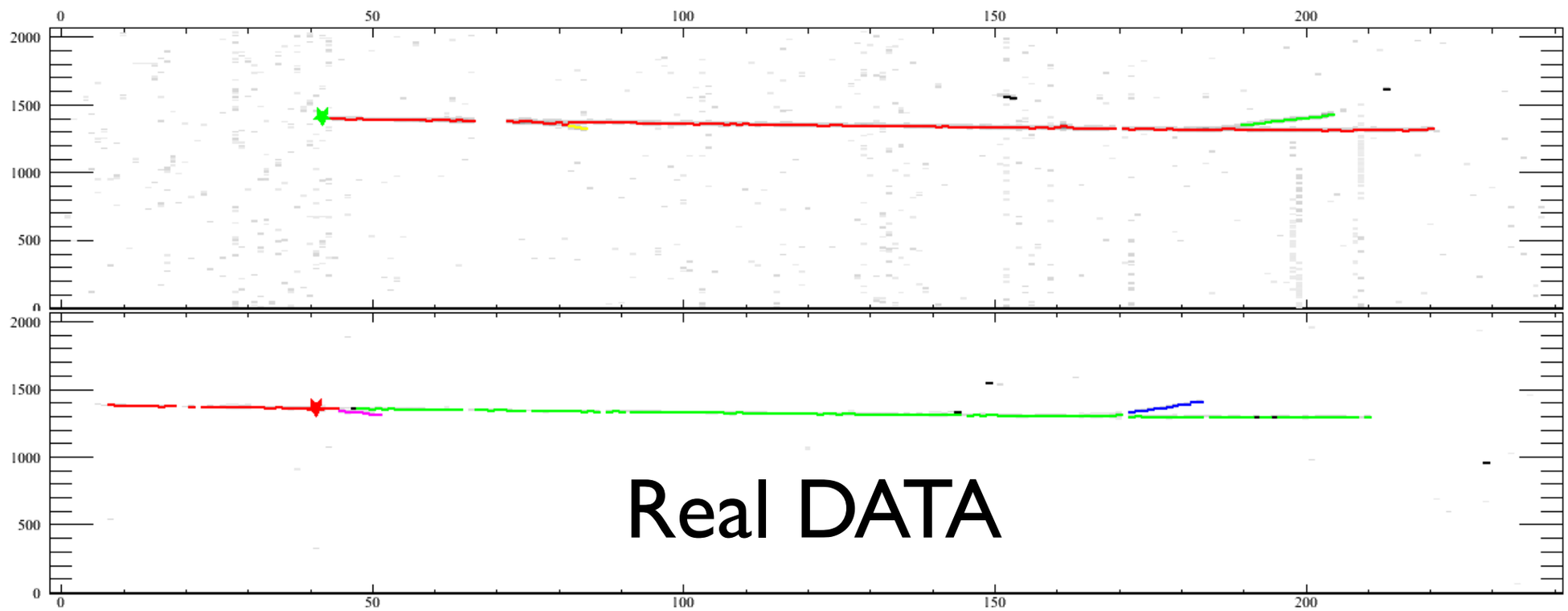


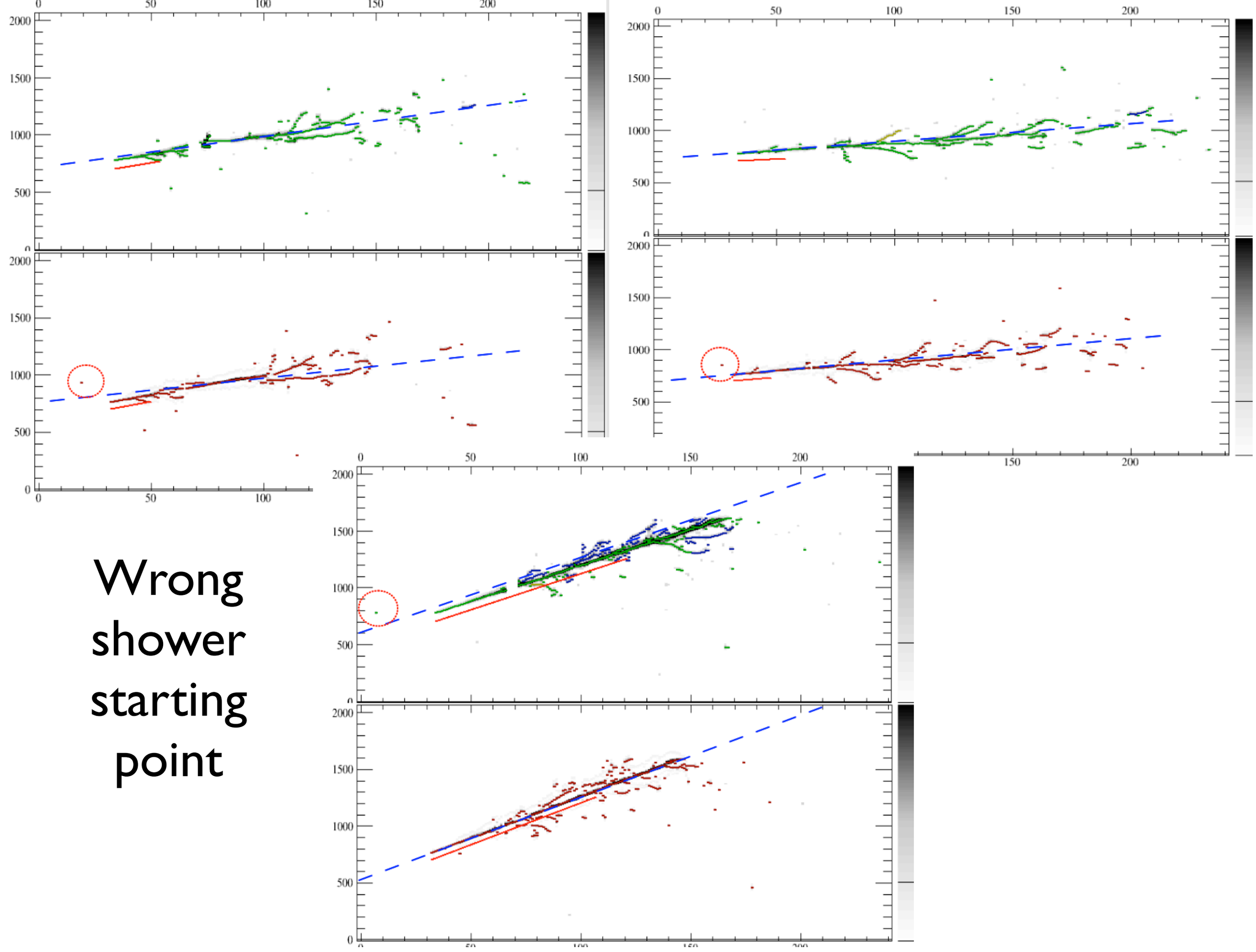
VERTEX RECONSTRUCTION





VERTEX RECONSTRUCTION





Wrong shower starting point

CLUSTERING

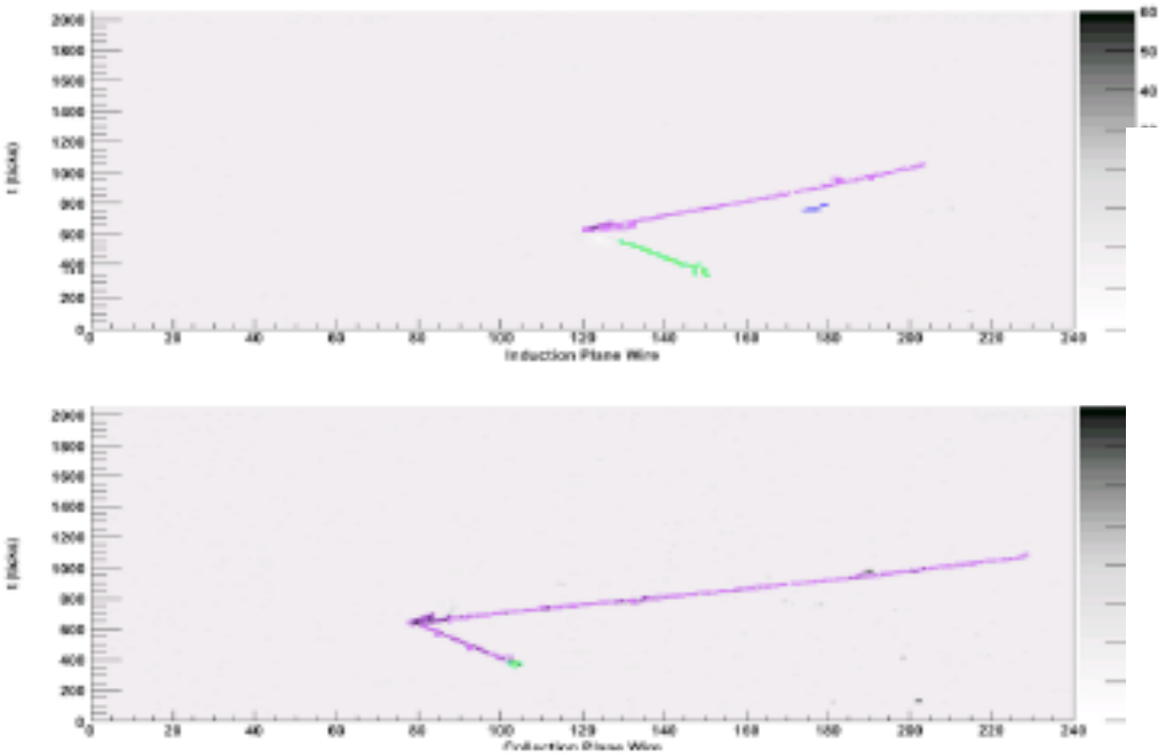


Figure 6.6: The DBSCAN clustering algorithm ran on a neutrino event. The display shows hits on the induction and collection plane, each color corresponds to a unique cluster forme

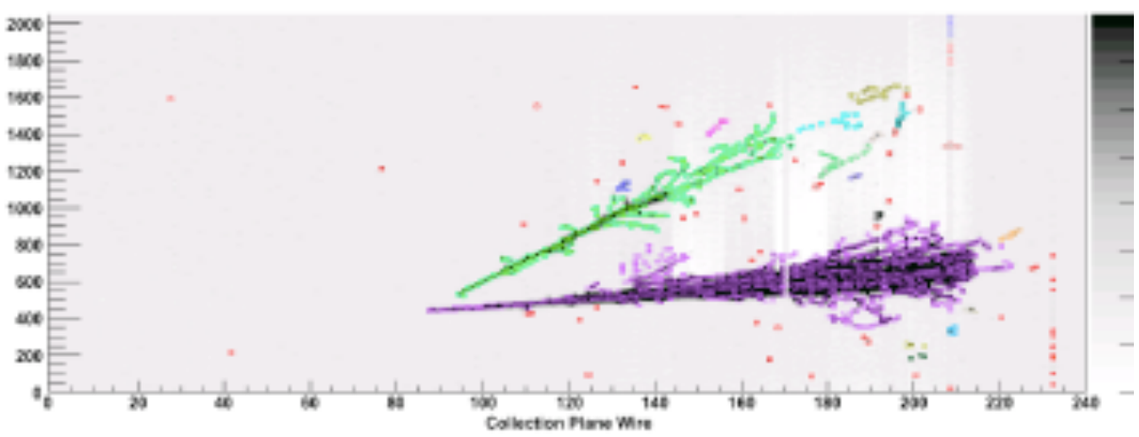


Figure 6.7: The DBSCAN clustering algorithm ran on a neutrino event. The display shows hits on the collection plane, each color corresponds to a unique cluster formed. The red hits r noise as decided by DBSCAN and are not passed to other algorithms.

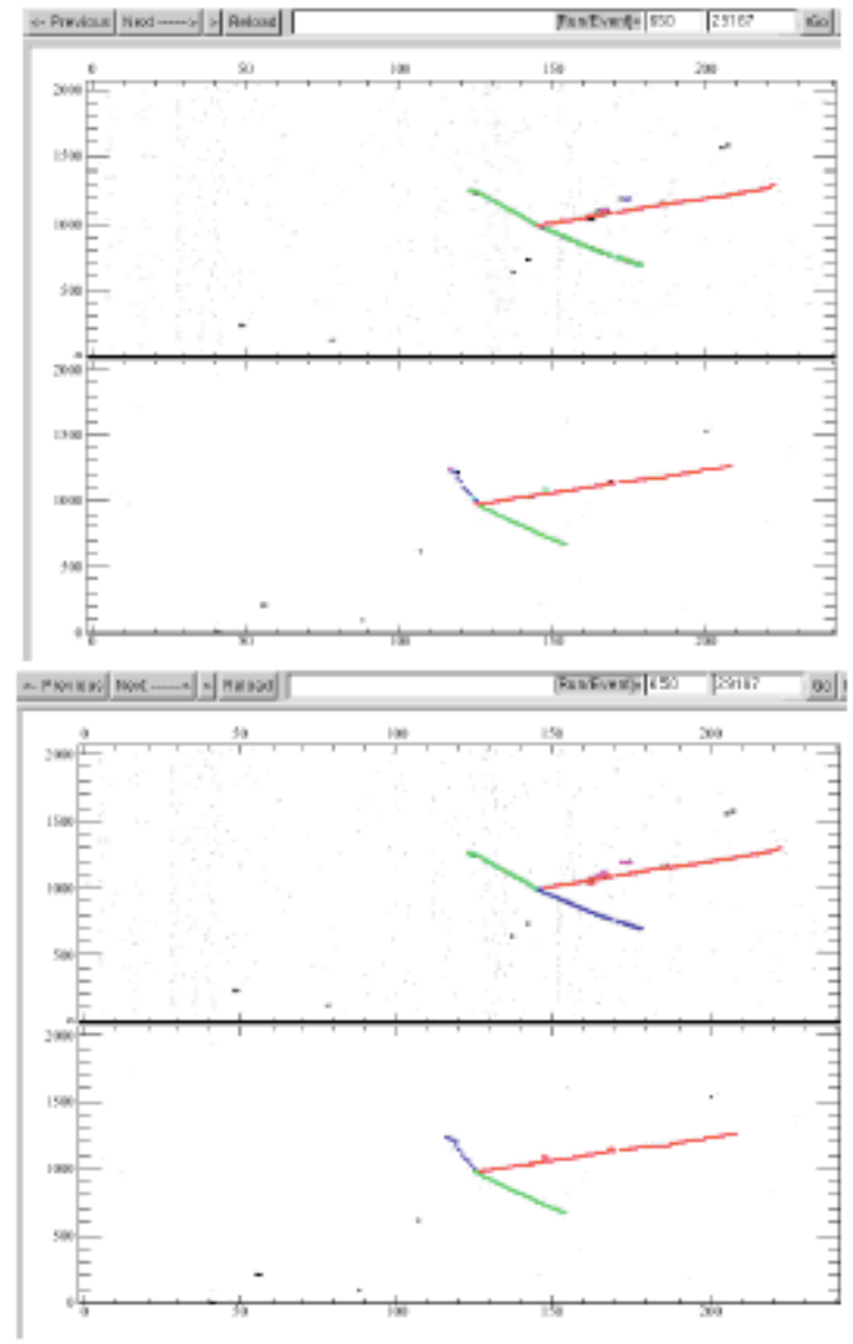
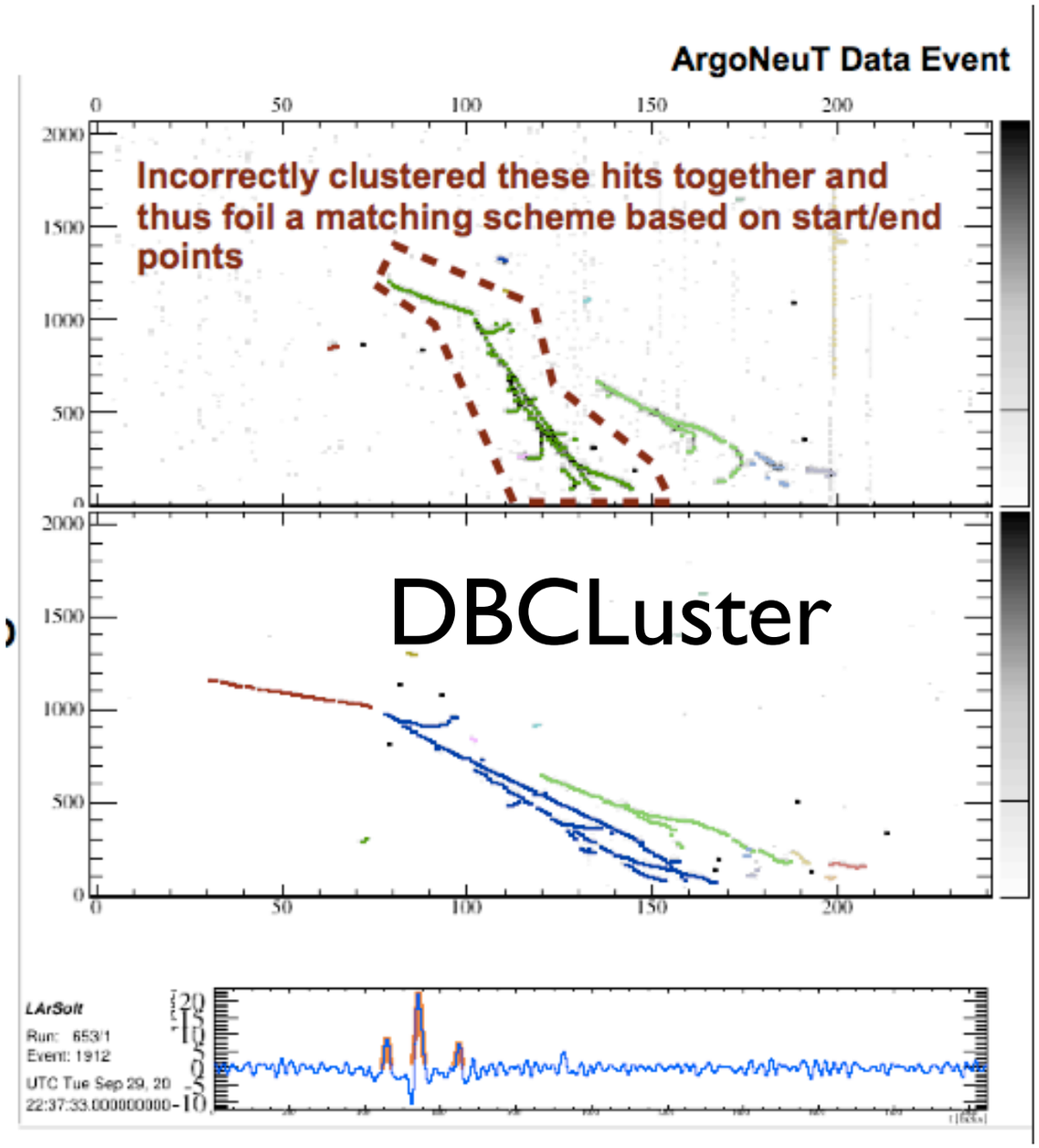
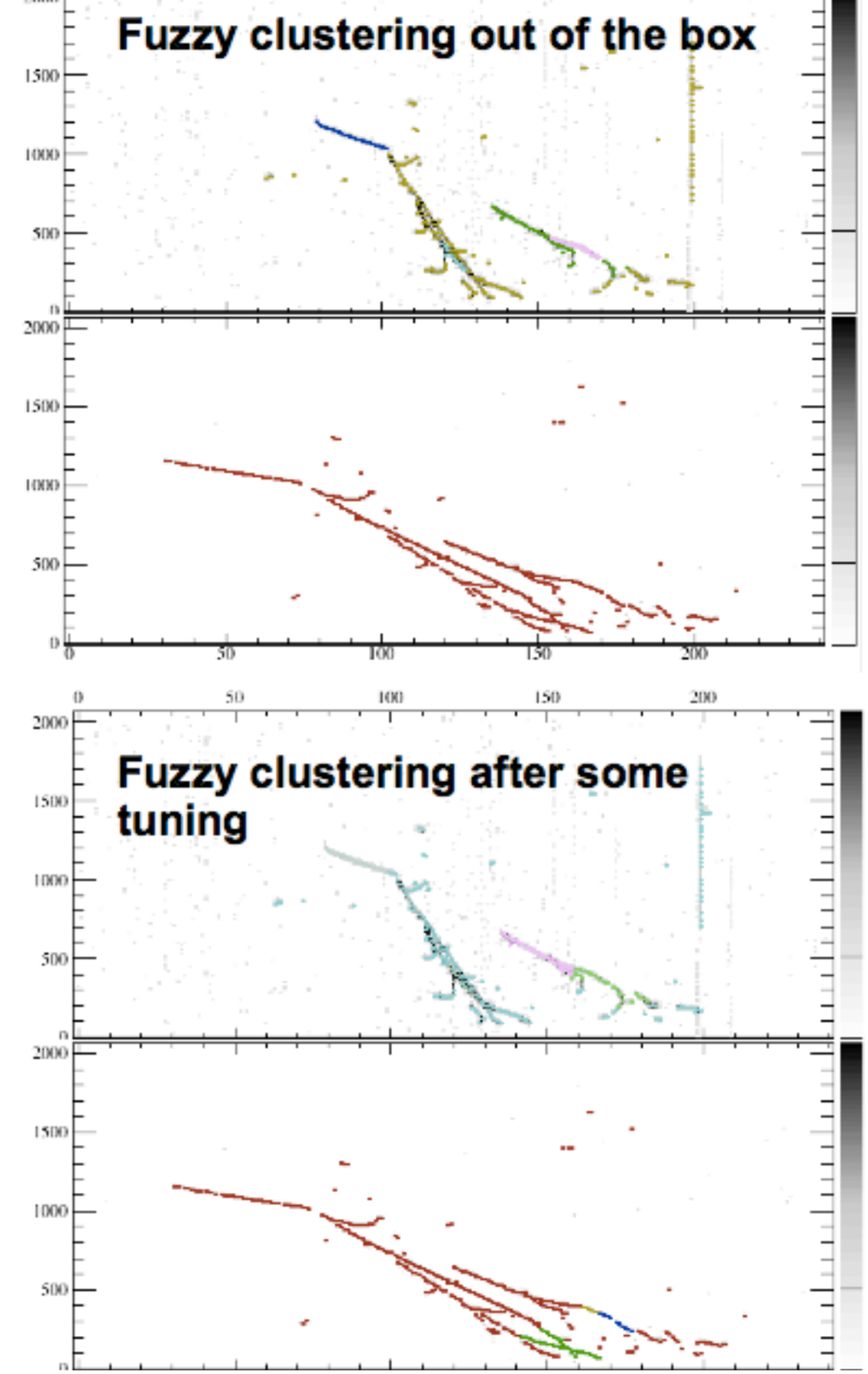


Figure 6.13: The event display showing LineMerger (top) and KingaCluster (bottom) ran on the same data event. In this case LineMerger merges two tracks as one on top plane while KingaCluster reconstructs them as separate clusters.

CLUSTERING





Note: The problems here with multiple clusters effect all subsequent tools that do shower analysis (ShowerAngleCluster, ShowerReco, etc...)

3D RECONSTRUCTION

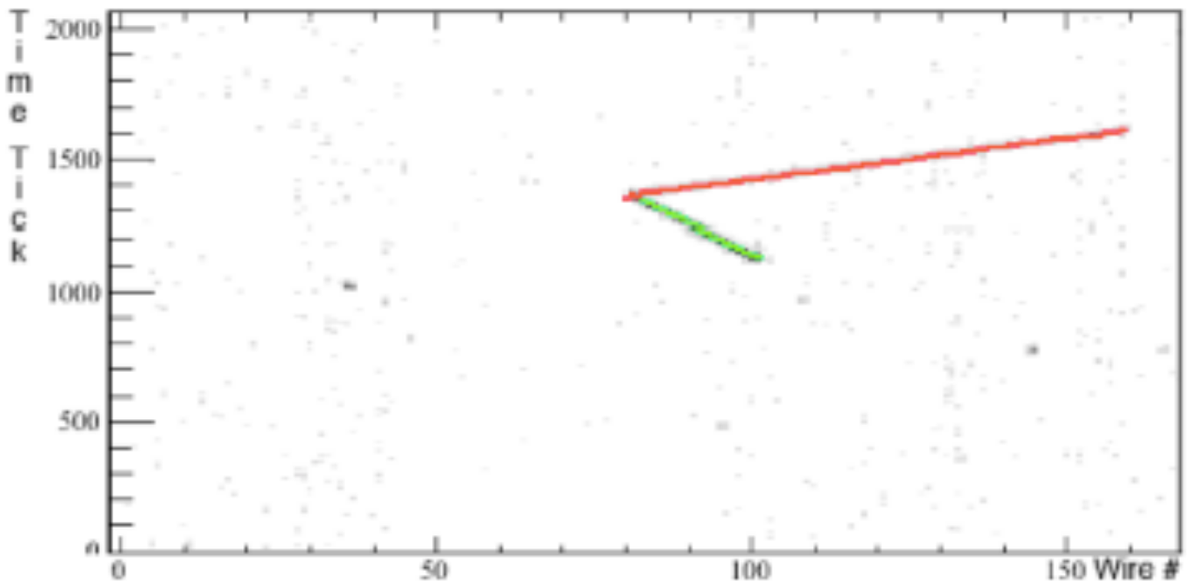


Figure 6.9: 2-dimensional clustering with Hough Transform on a ArgoNeuT neutrino event. The reconstructed hits are visible in gray, while the two colors represent the clustered lines corresponding to 2-dimensional tracks.

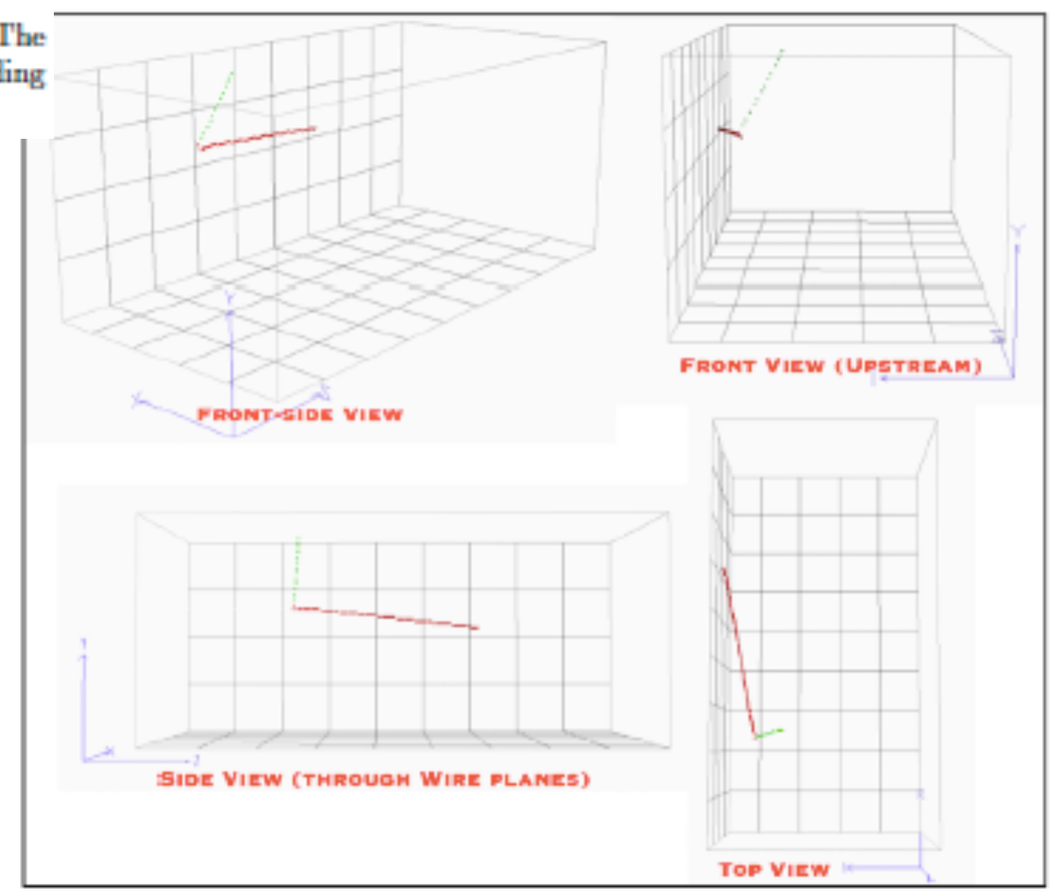
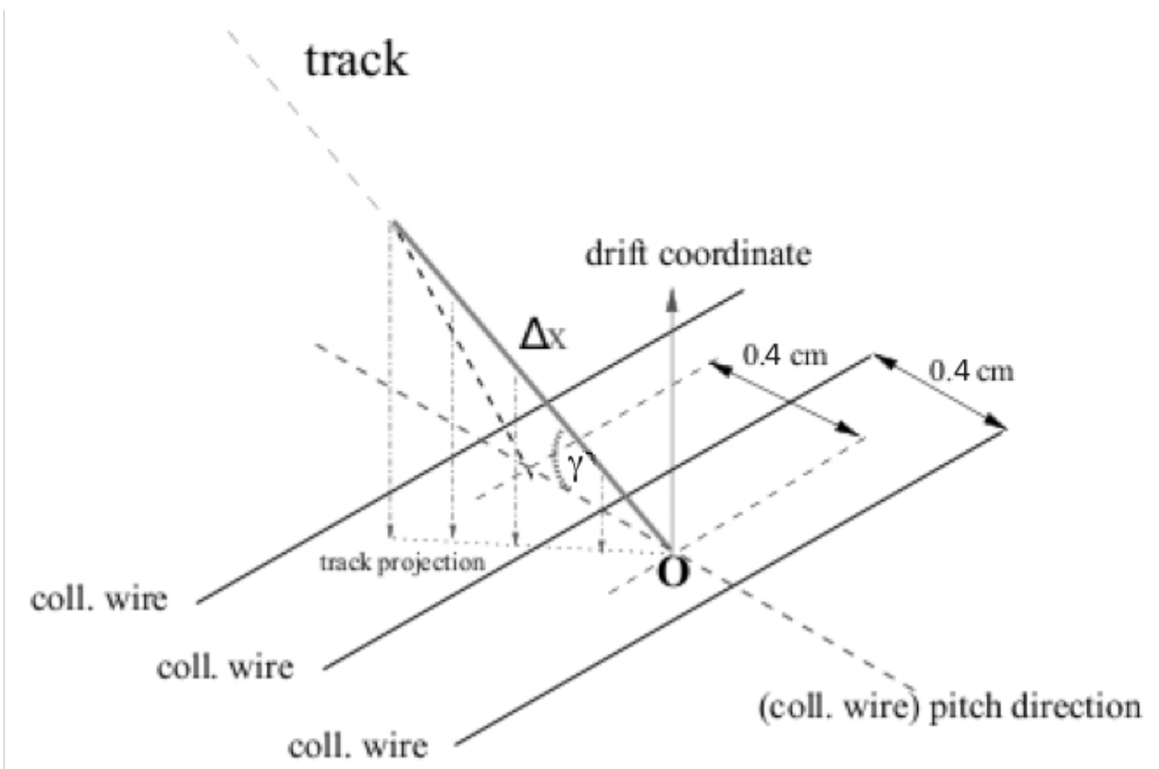


Figure 6.15: Different views of a reconstructed neutrino event in three dimensions. The longest track is seen to be exiting the TPC volume through the cathode plane.

Calorimetric reconstruction (I)

- After the 3D geometric reconstruction, determination of the energy release in LAr is performed by the further steps:
  1. account for the charge loss due to electro-negative impurities
  2. charge to energy conversion with correction for the quenching effect

❑ The hit amplitude dQ (in units of ADC counts) is normalized for the track pitch length (i.e. the effective length of the portion of track exposed to a single wire, depending on the orientation of the track with respect to the direction of the wires in the plane) dQ/dx [ADC/cm]



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Calorimetric reconstruction (II)

- An electronic calibration factor

  f_{Cal}=7.54 ADC/fC (for ArgoNeuT)

  is applied to convert from ADC count to charge expressed in number of electrons dQ/dx [e/cm]

1. To account for the charge loss along the drift due to electro-negative impurities the charge dQ/dx [e/cm] is multiplied by $e^{(t-t0)/\tau}$,where $(t-t_0)$ is the hit drift time and τ is the measured electron lifetime (measured run by run, ~750 μs for ArgoNeuT @ NuMI – ν mode).

2. The full calorimetric reconstruction is performed accounting for the quenching effect on the ionization charge, using Birks model, to convert dQ/dx [e/cm] to energy released per unit length dE/dx [MeV/cm]. From the parameterization of the recombination formula in ICARUS, NIM 523 (2004), 275:

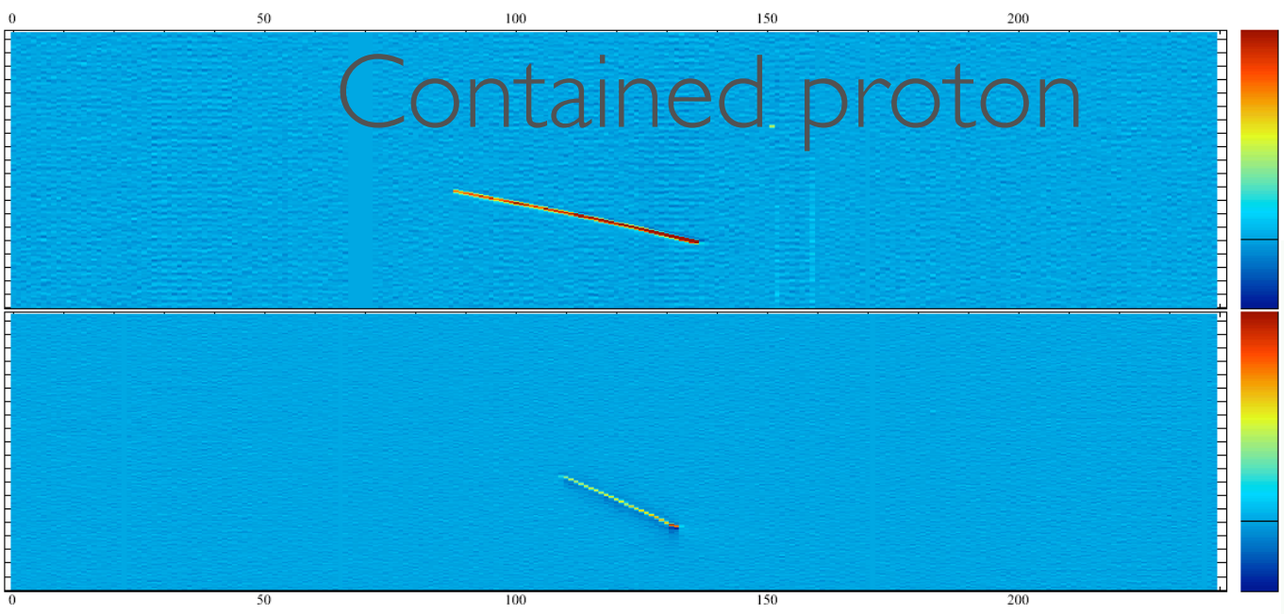
$$\frac{dE}{dx} = \frac{\frac{dQ}{dx}}{\frac{A}{W_{ion}} - \frac{K}{E_{Field}}\frac{1}{\rho}\frac{dQ}{dx}}$$

$A_{3t} = 0.800 \pm 0.003,$

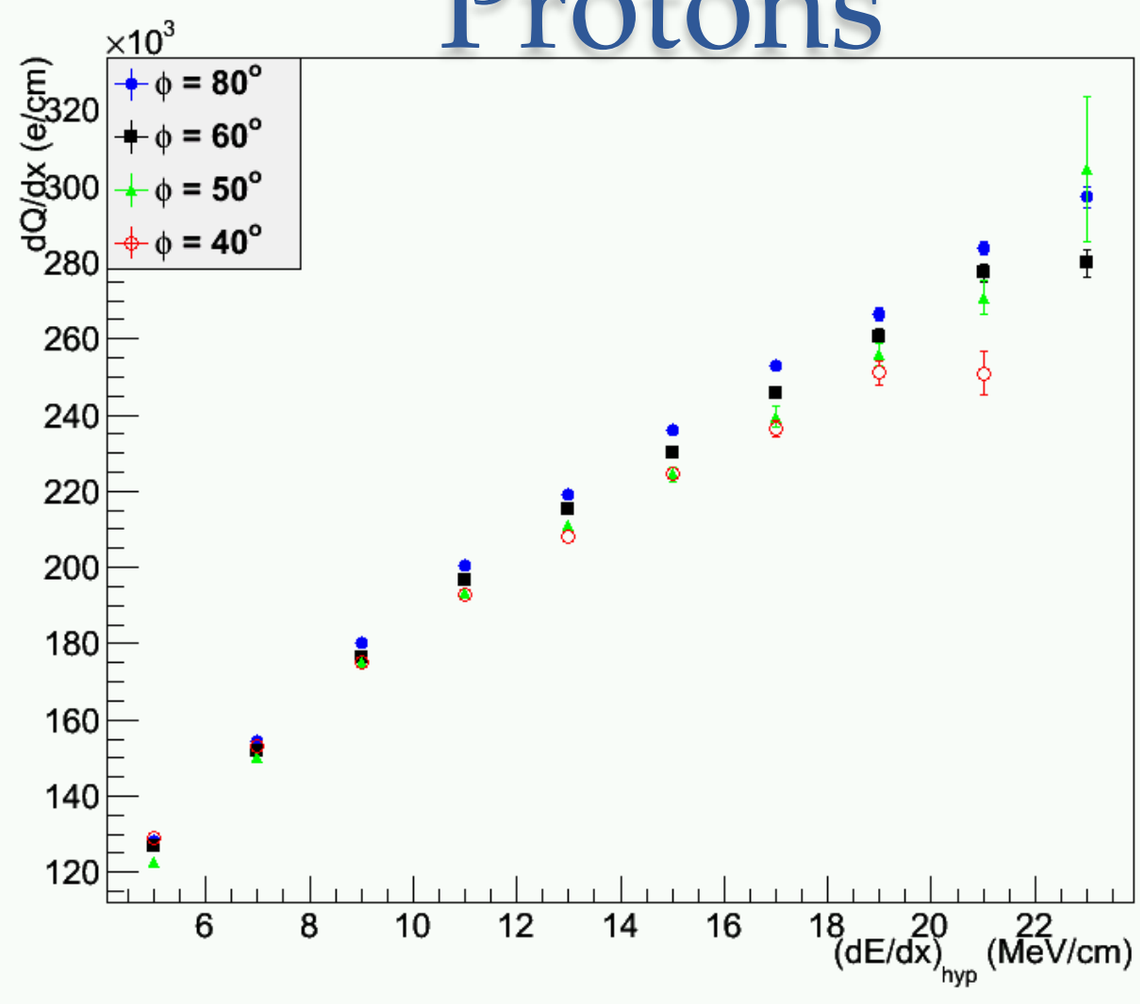
$k_{3t} = 0.0486 \pm 0.0006 \text{ kV/cm} \frac{\text{g/cm}^2}{\text{MeV}}$

depends on the ionization density (dQ/dx)

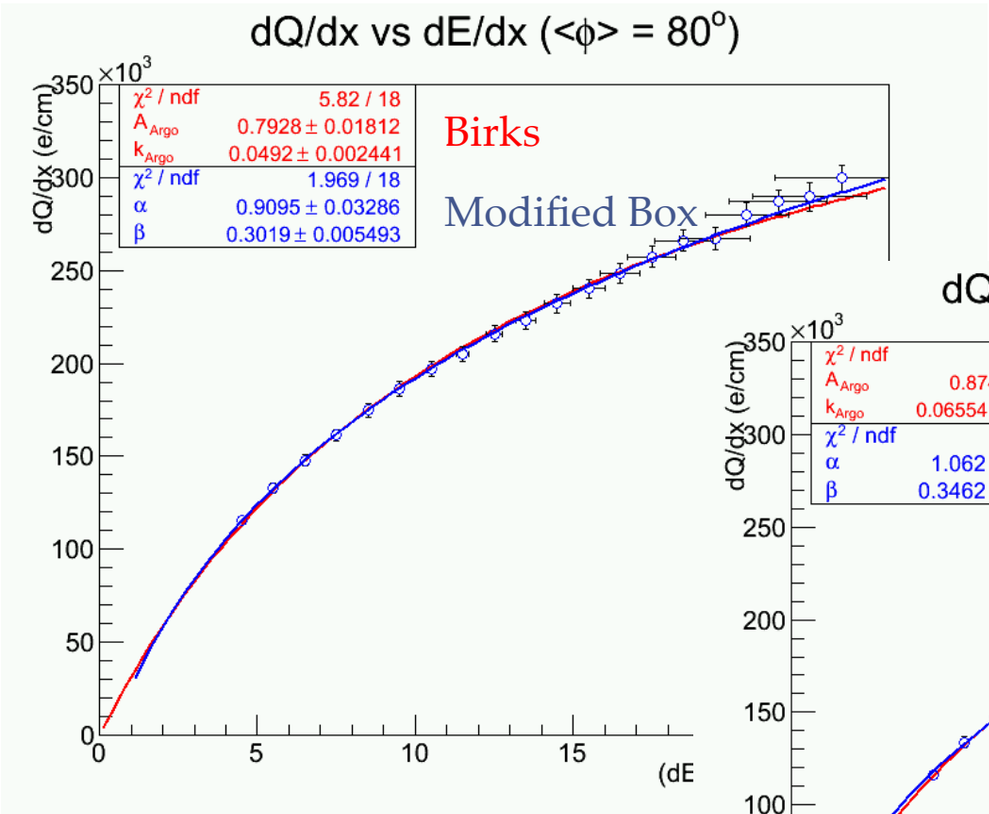
A study of electron recombination using highly ionizing particles in ArgoNeuT



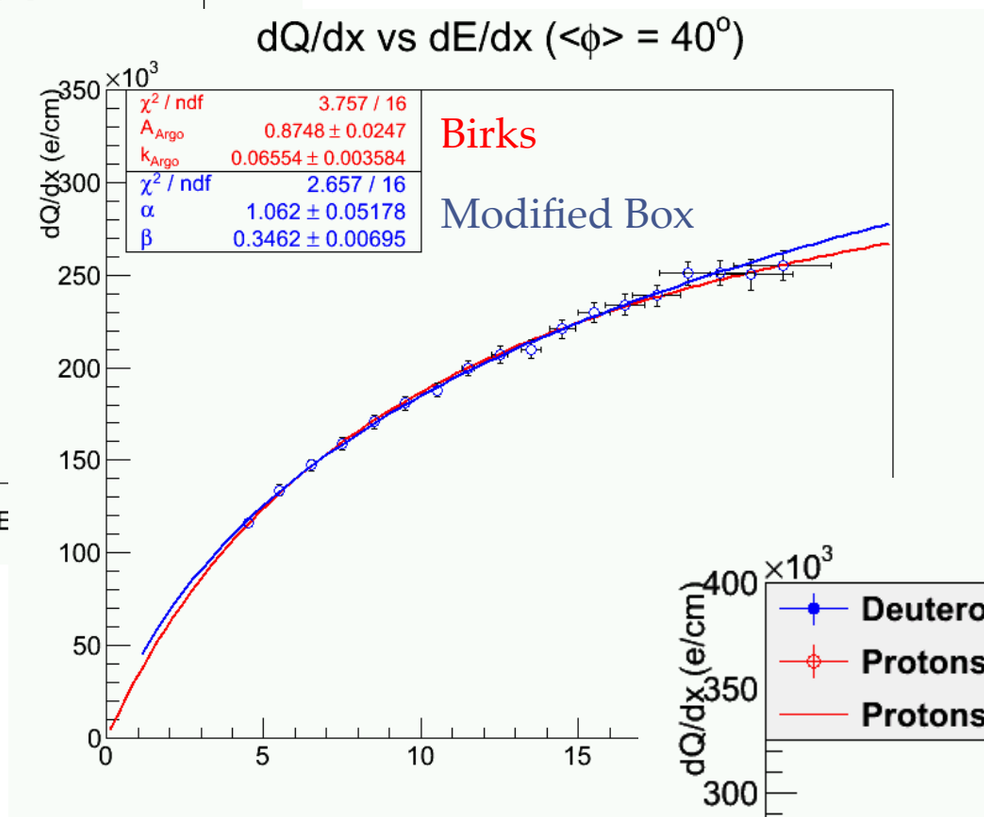
Angular Dependence Protons



Recombination Fits

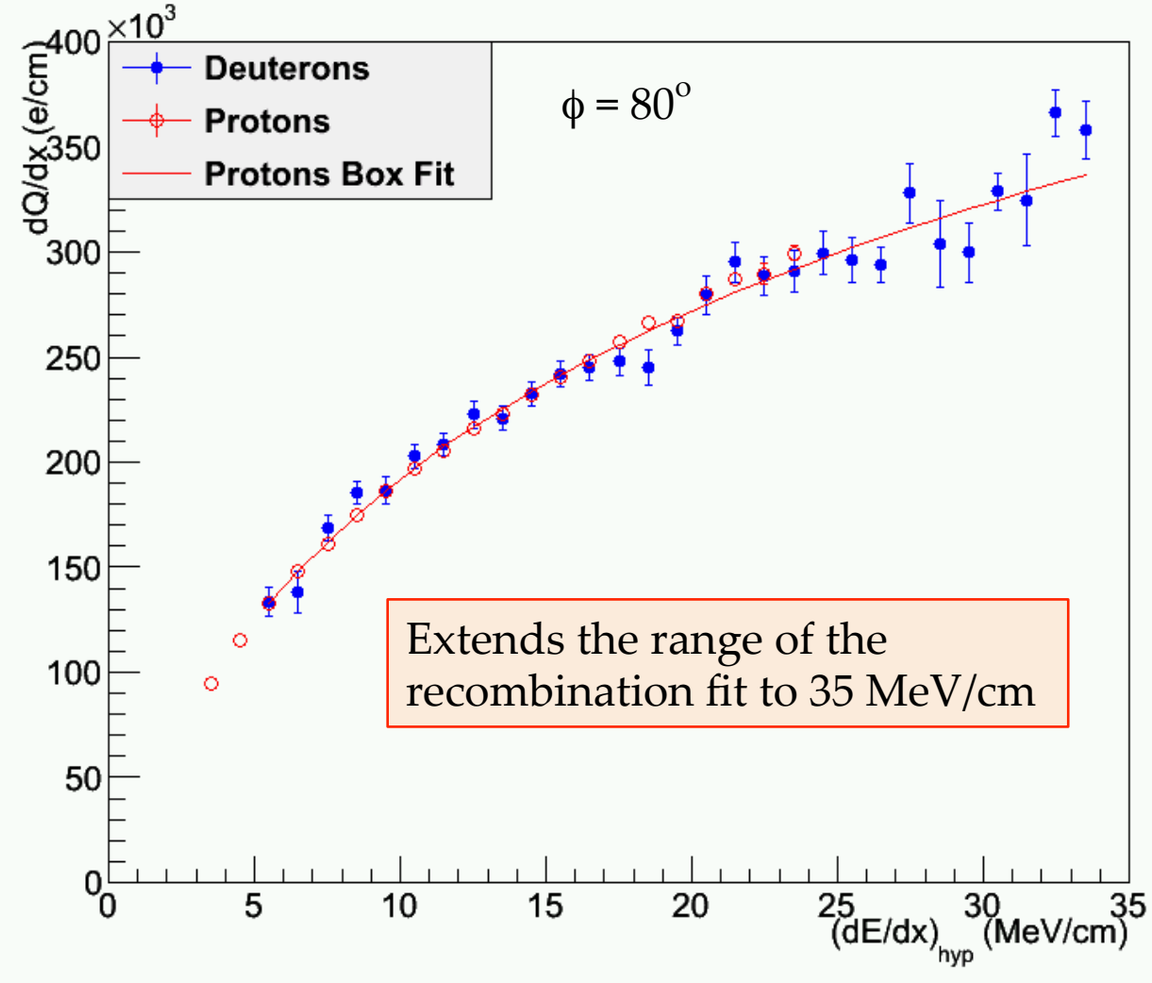


Vertical bars include 2% systematic error



Data – open circles
Birks fit – red curve
Modified Box fit – blue curve

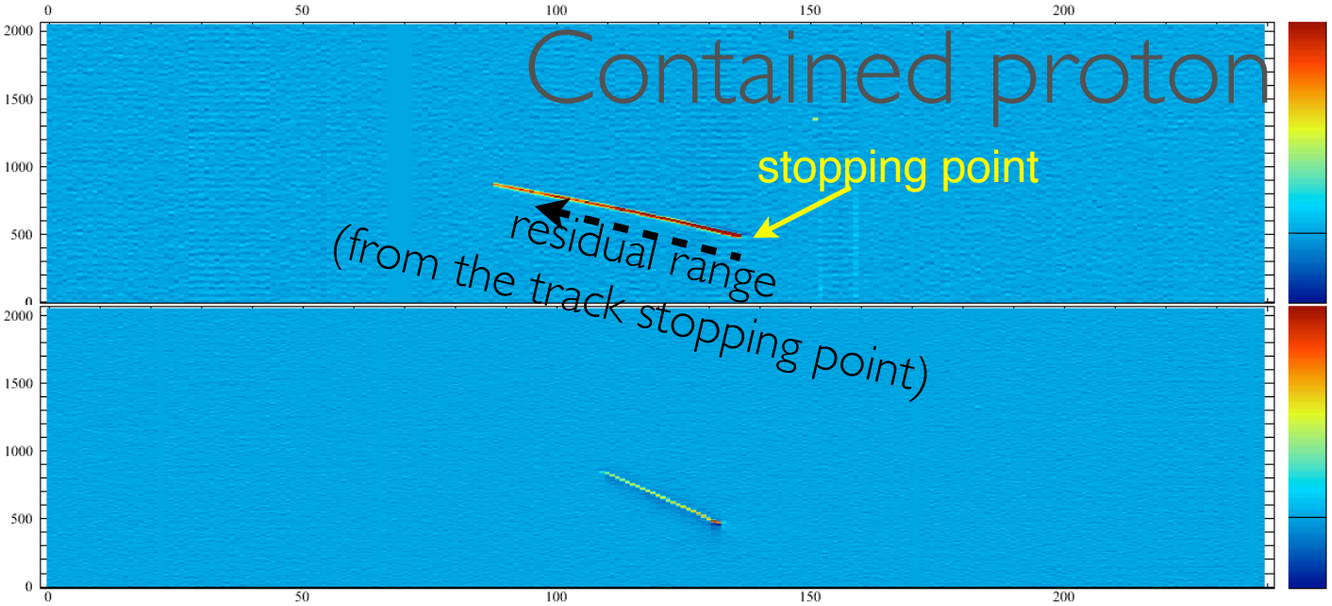
Deuterons



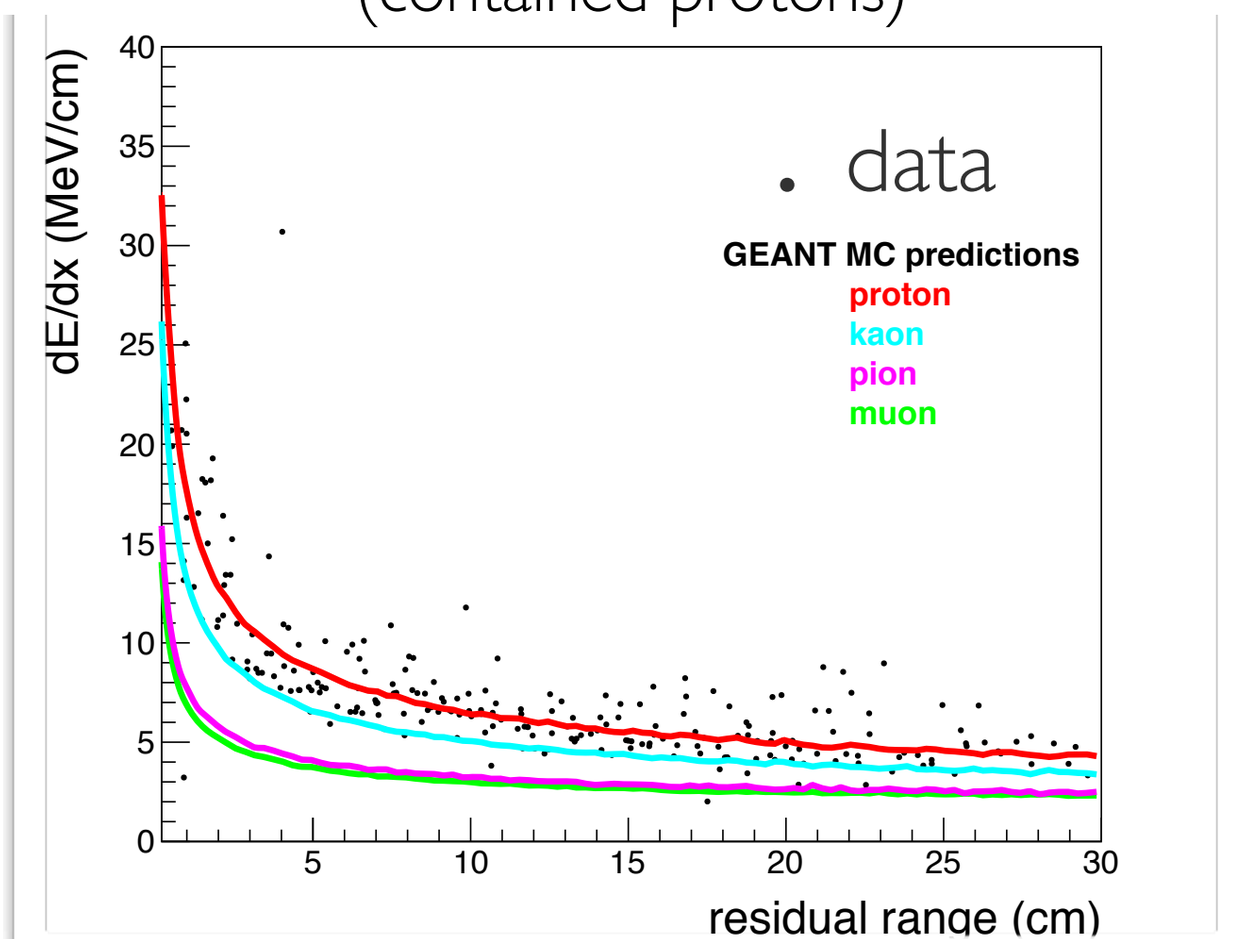
Extends the range of the recombination fit to 35 MeV/cm

Birks model diverge for high ionization, Birks model solve this problem, new measurement from ArgoNeuT

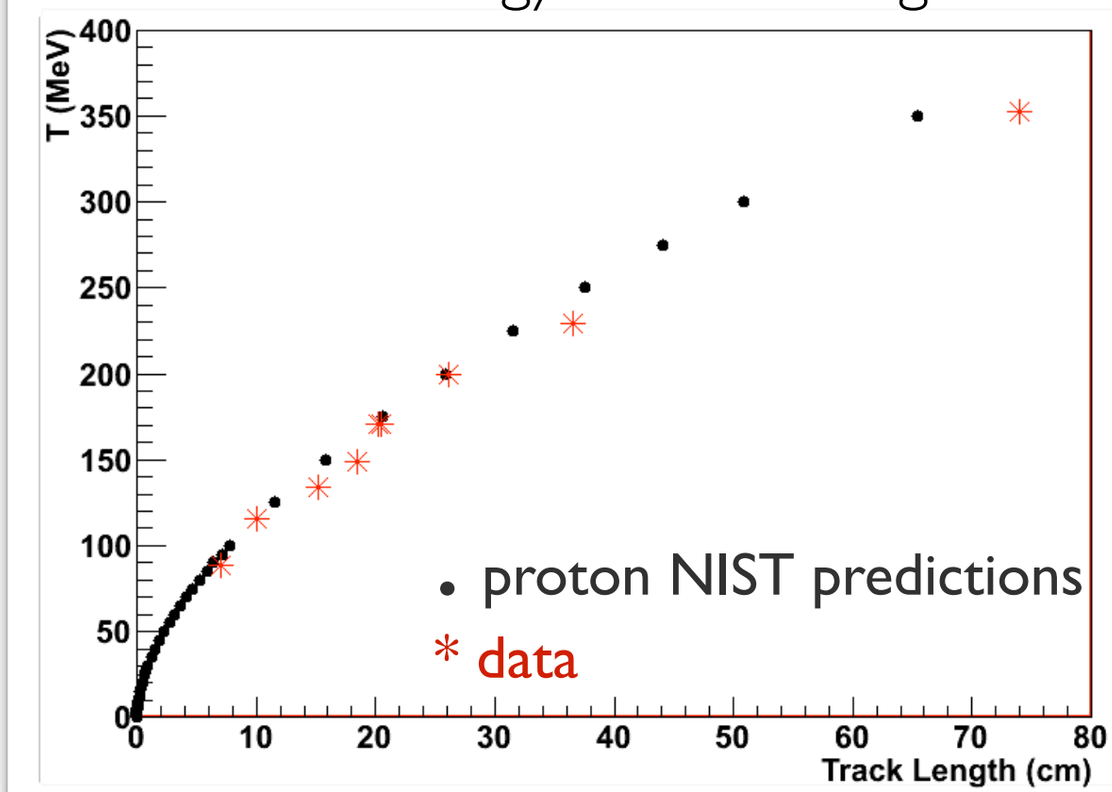
STOPPING TRACKS - CALORIMETRIC RECONSTRUCTION and PID



dE/dx vs. residual range
(contained protons)

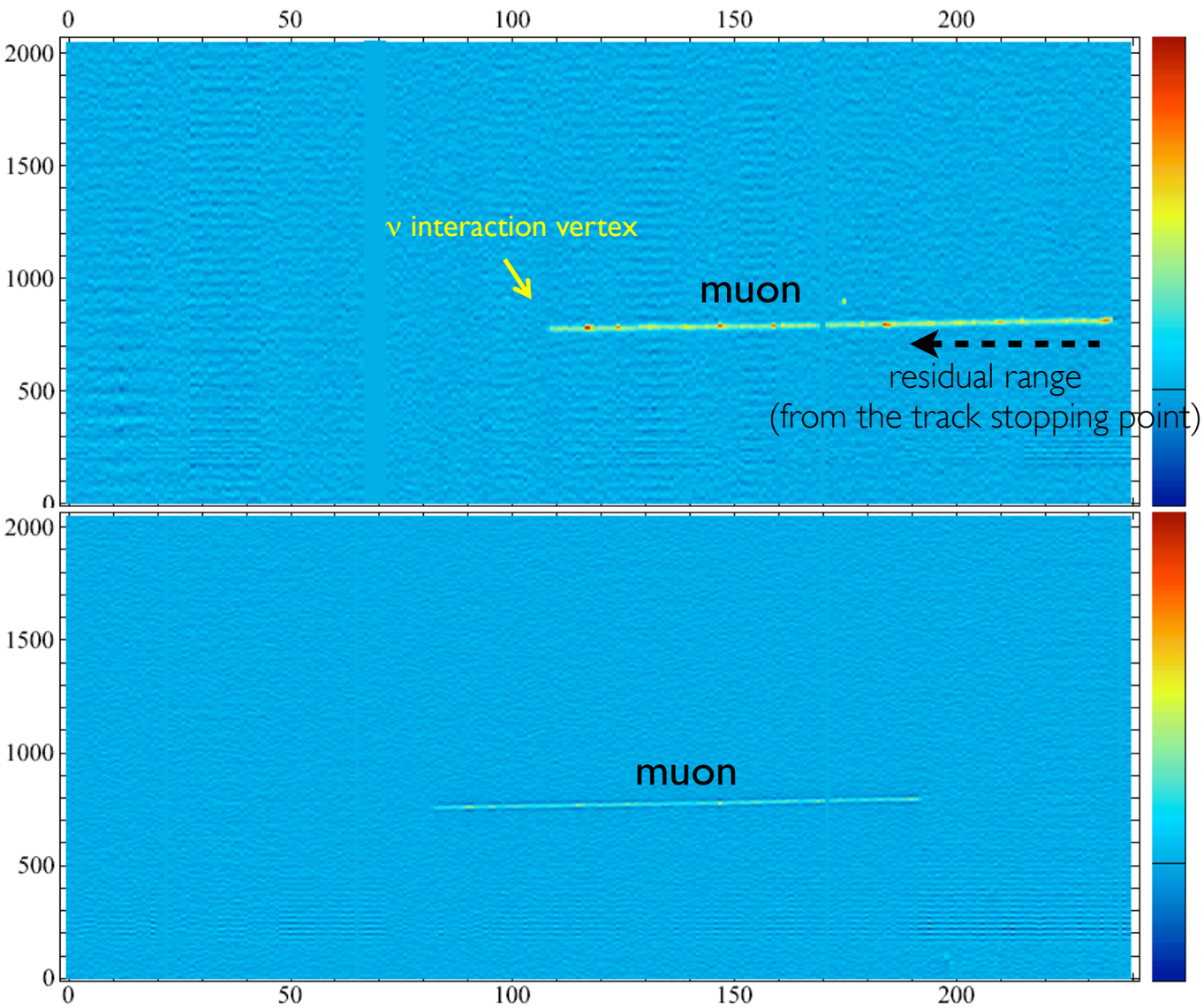


Kinetic Energy vs. track length



Measurement of:

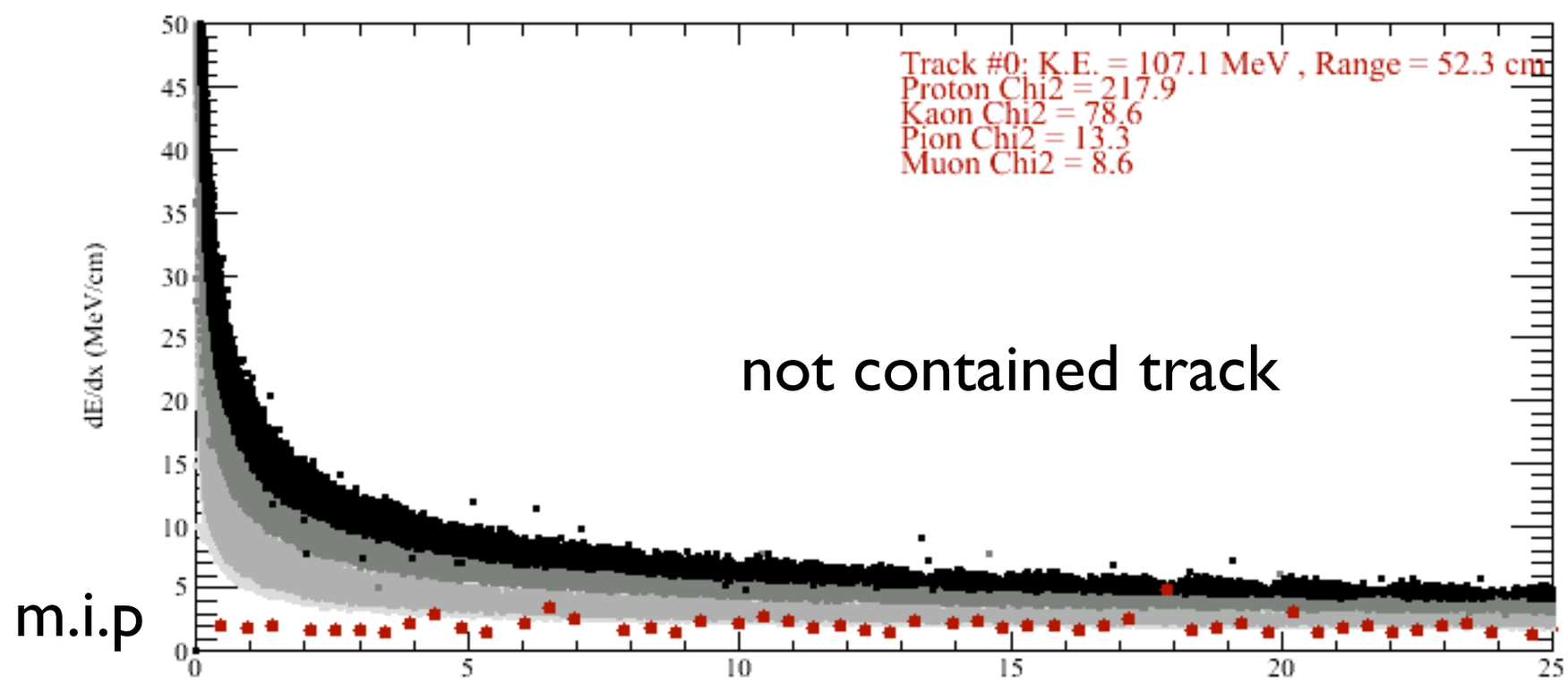
- dE/dx vs. residual range along the track
- kinetic energy vs. track length



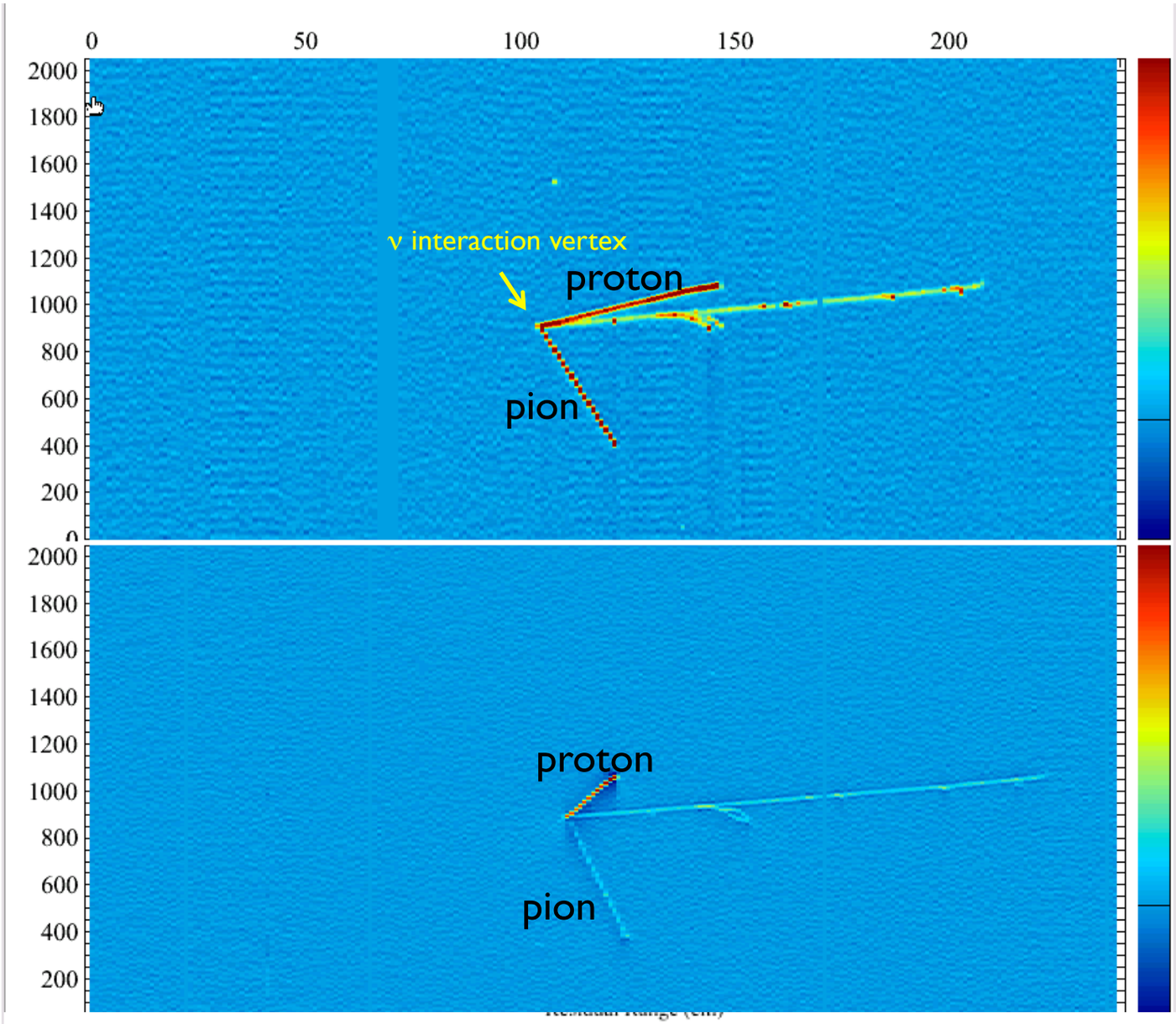
0p event

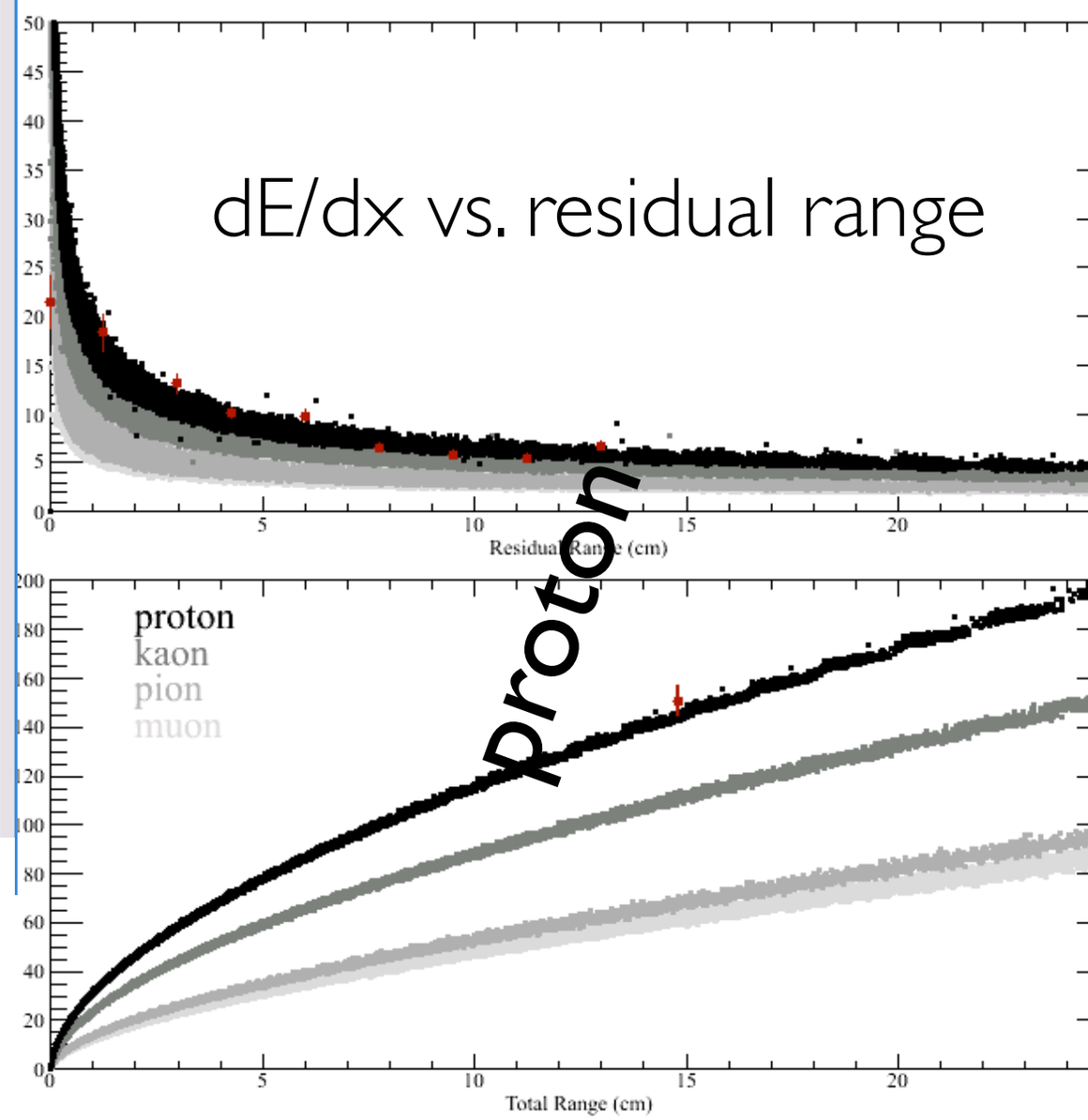
not contained muon (m.i.p.): flat dE/dx vs. res. range

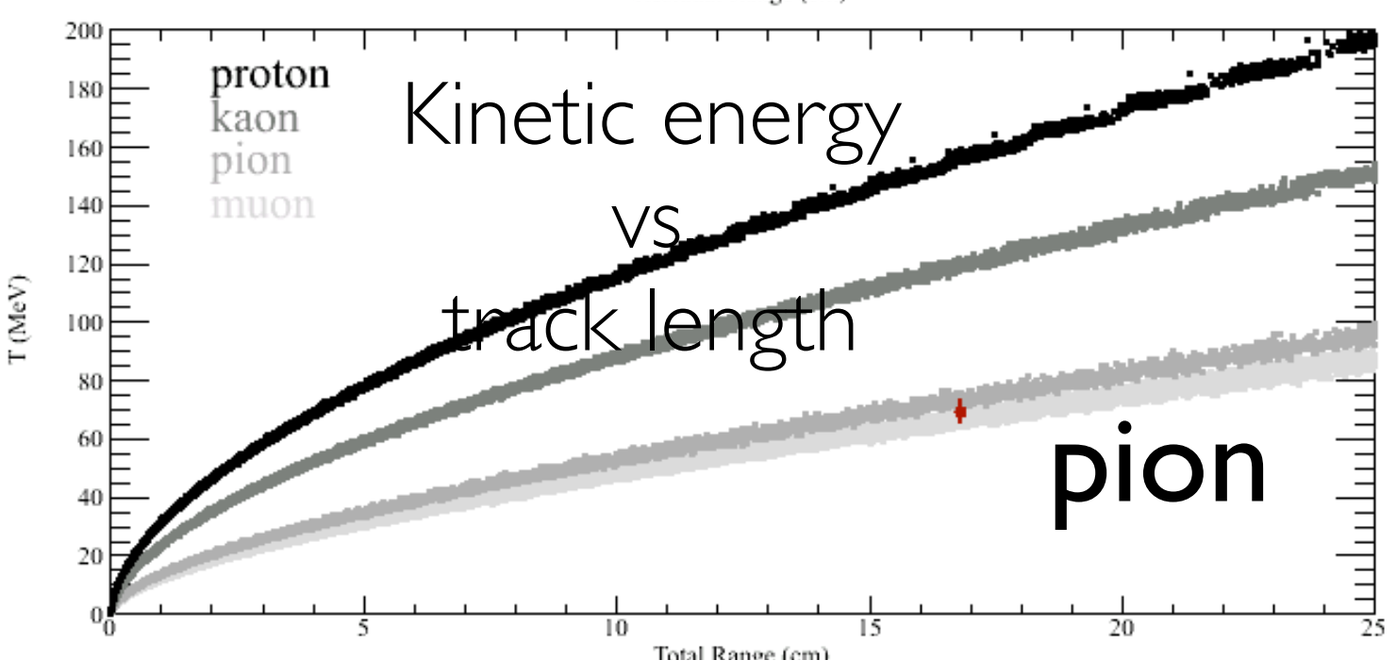
dE/dx vs. residual range



μ+Np+1π events

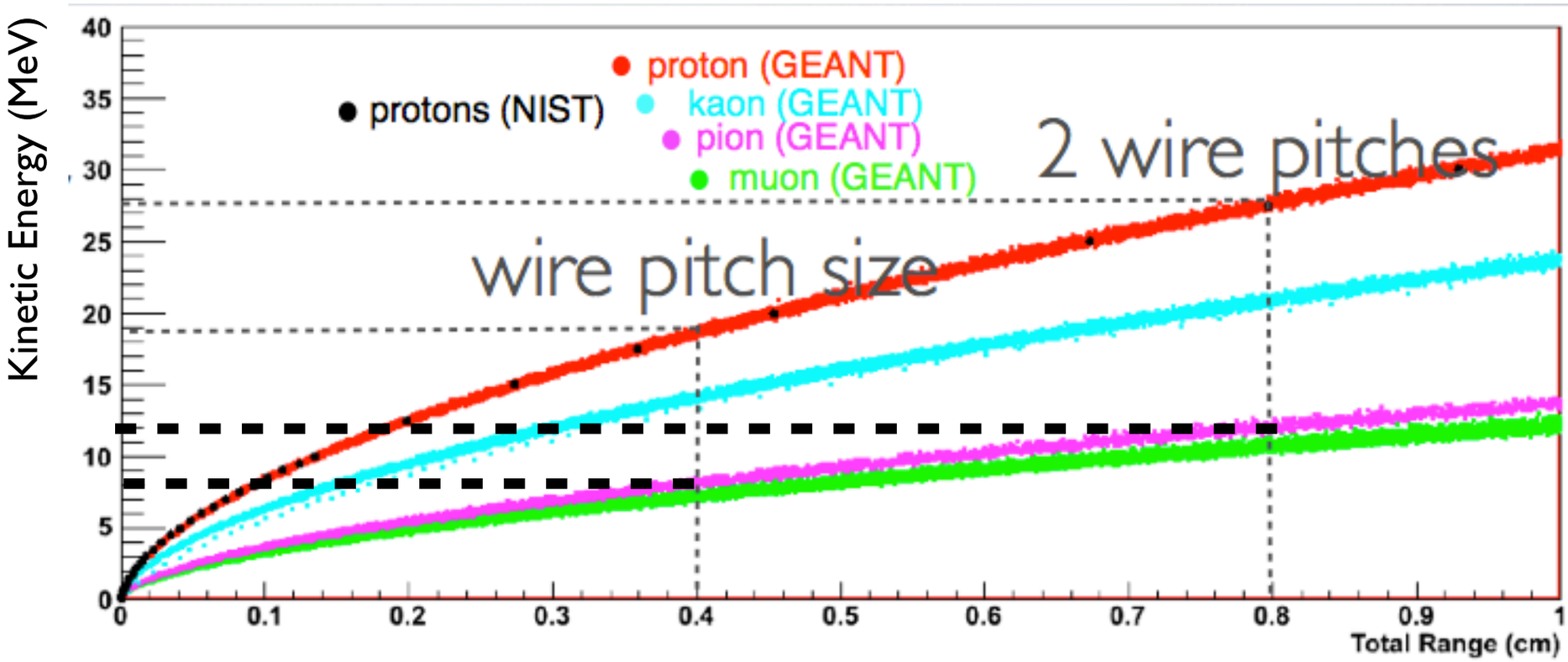






Analysis in progress

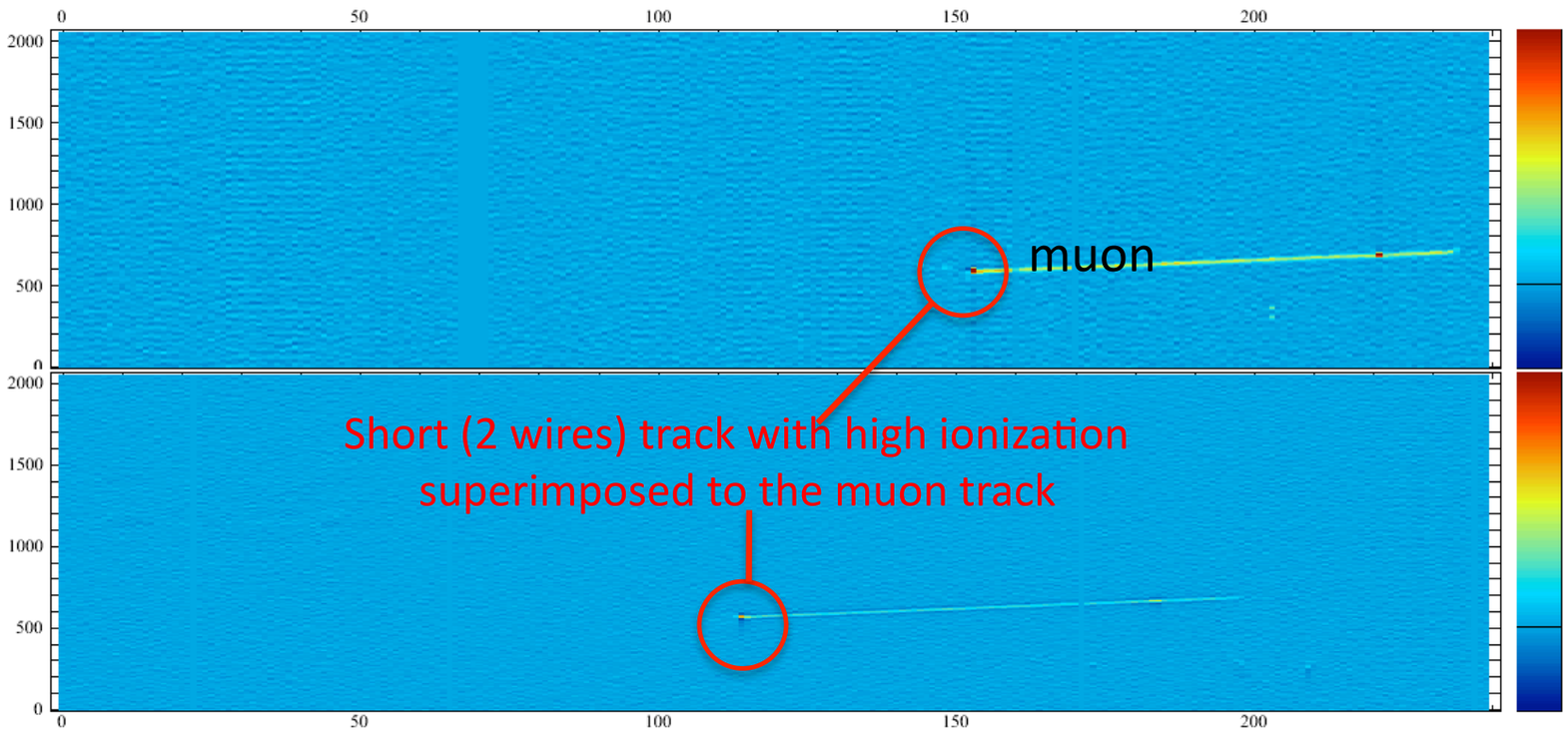
Kinetic energy vs range in LAr



wire pitch of 0.4 cm corresponds to ~ 19 MeV for protons and
~ 8 MeV for pions

wire pitch of 0.8 cm corresponds to ~ 27 MeV for protons and
~ 12 MeV for pions

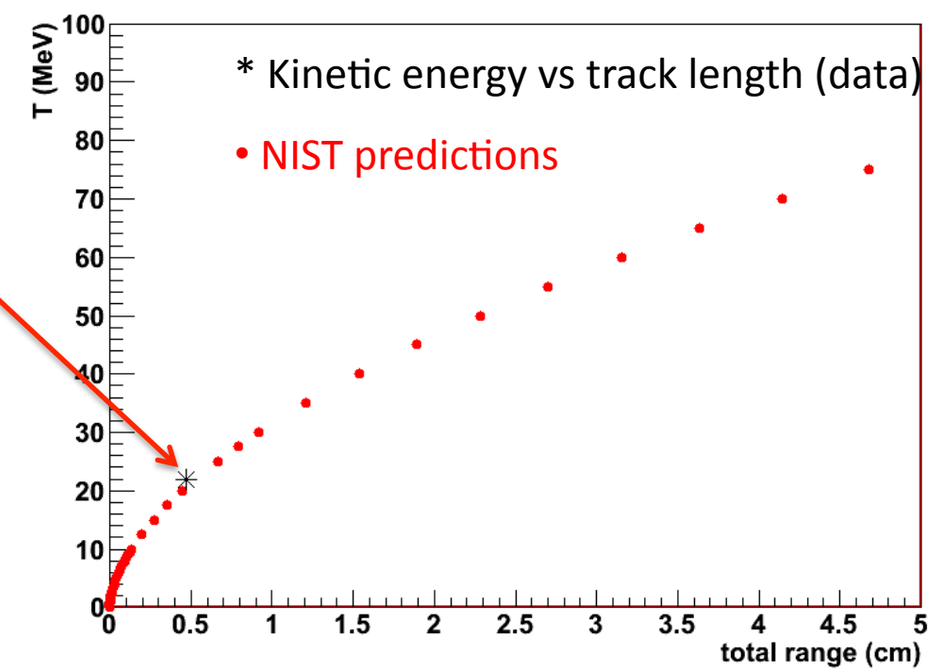
Example of Low energy proton reconstruction



The short track behaves like proton

Length=0.5 cm

KE=22±3 MeV



ArgoNeuT proton reconstruction threshold is 21 MeV of Kinetic Energy

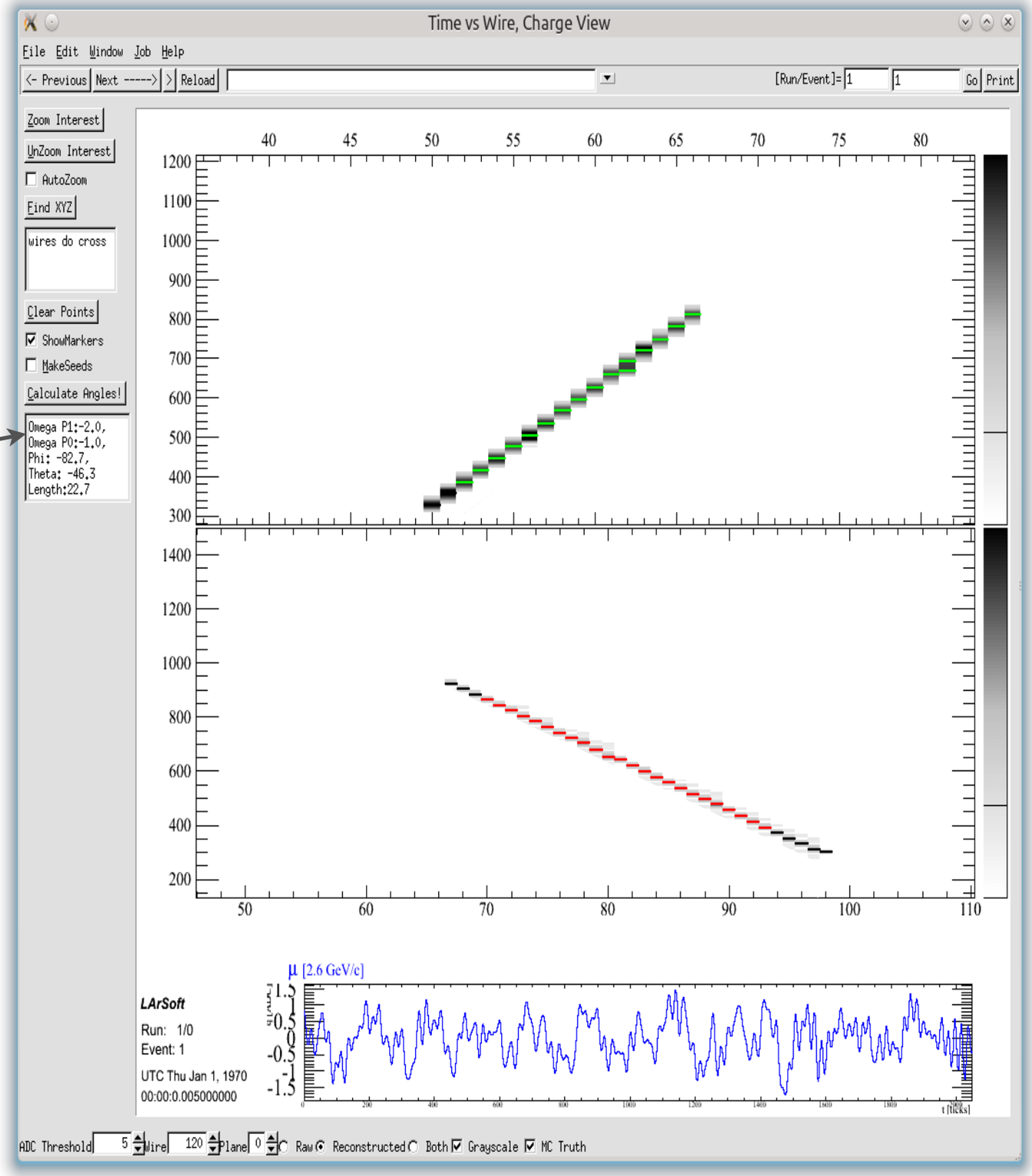
EVD ANALYSIS TOOL

The user selects a line with the mouse.

The EVD selects nearest hits along the line. 3D and Calorimetric reconstruction of the selected hits is performed.

add/remove hits with mouse

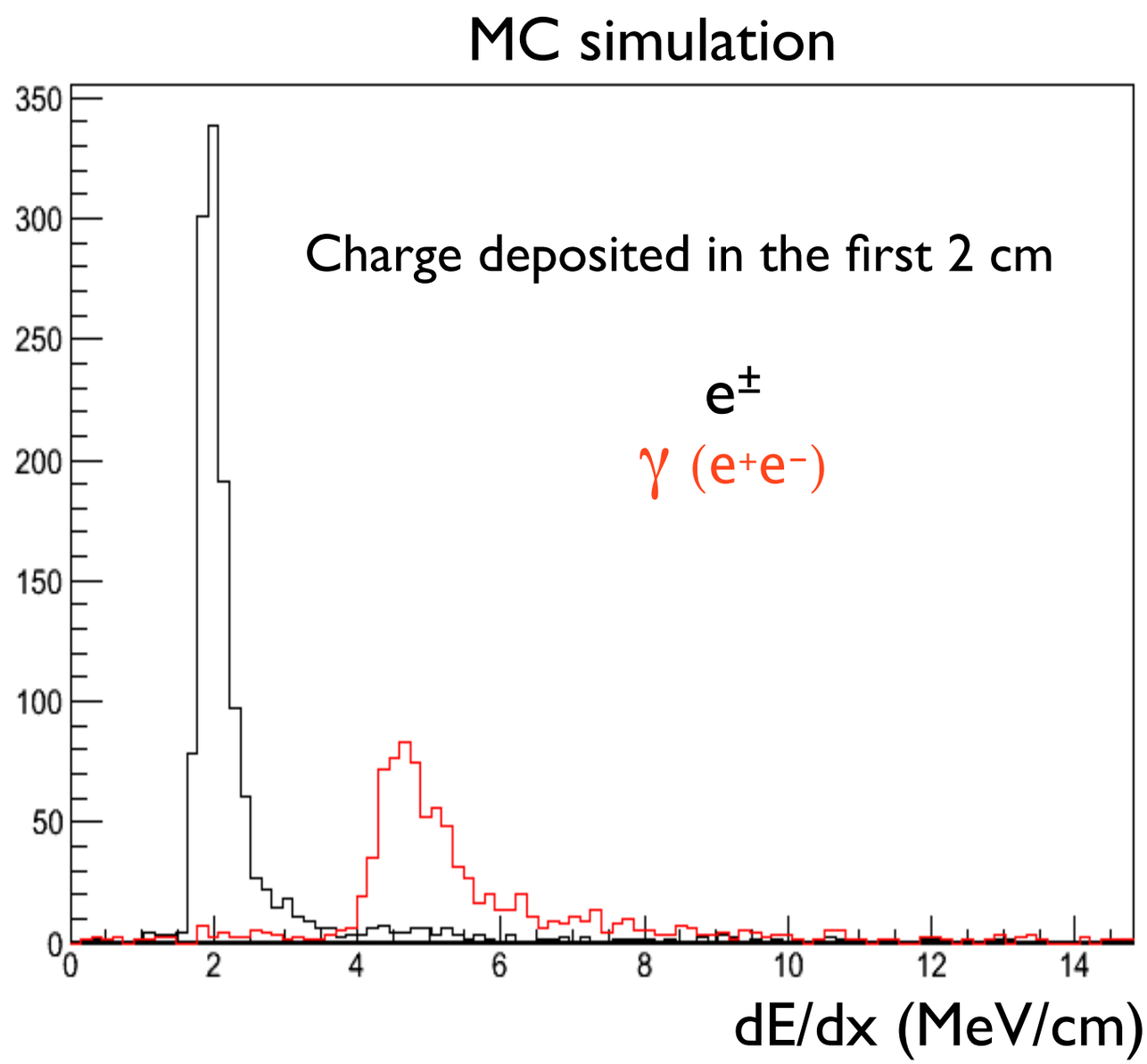
Calorimetry/PID display



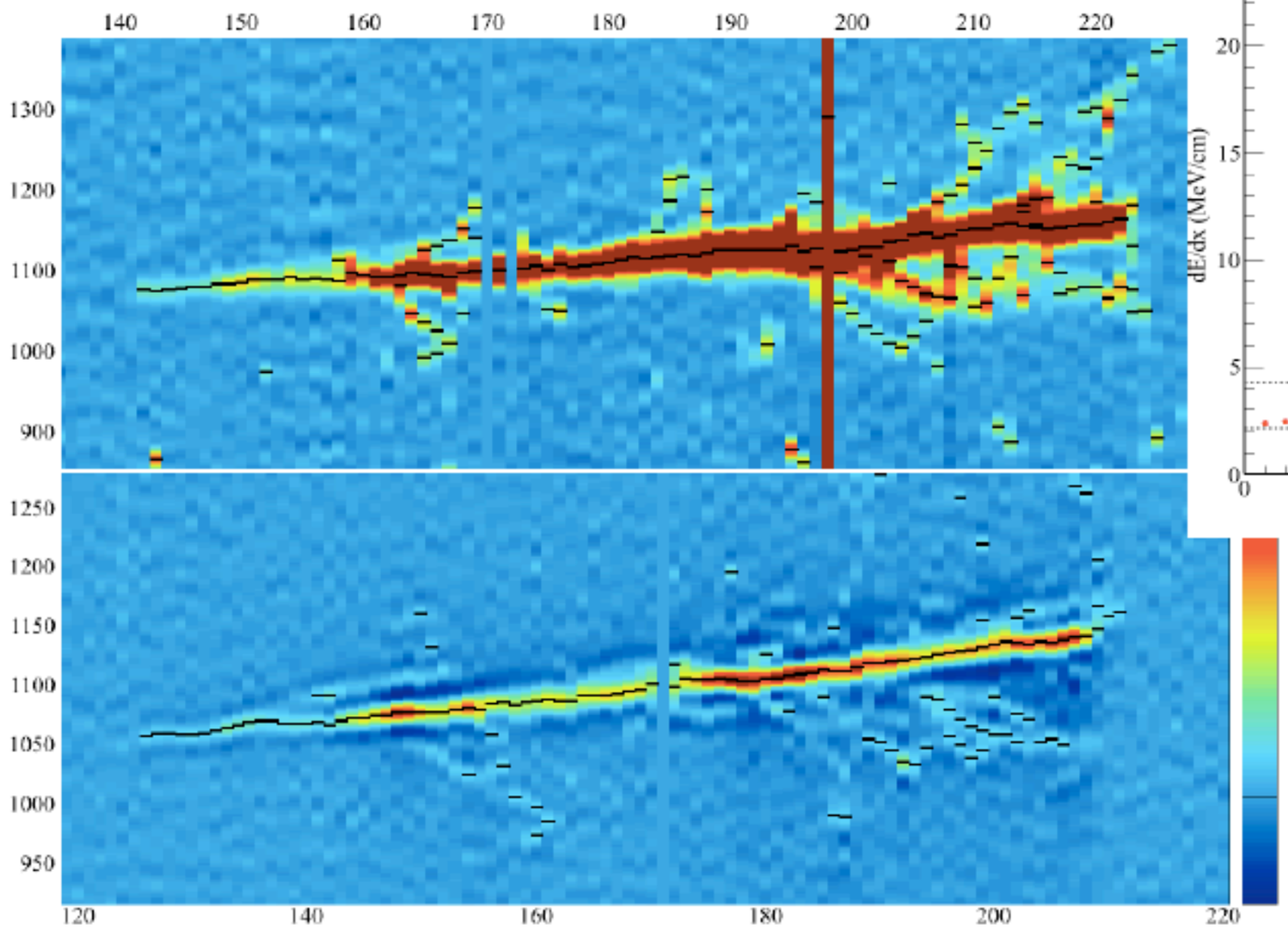
each candidate proton track is reconstructed by manually picking out hits belonging to it and passing them as input clusters to the three-dimensional tracking algorithm, calorimetric reconstruction and PId. It is a very lengthy process, requiring great care of selecting each hit, that is especially important for events having very short tracks.

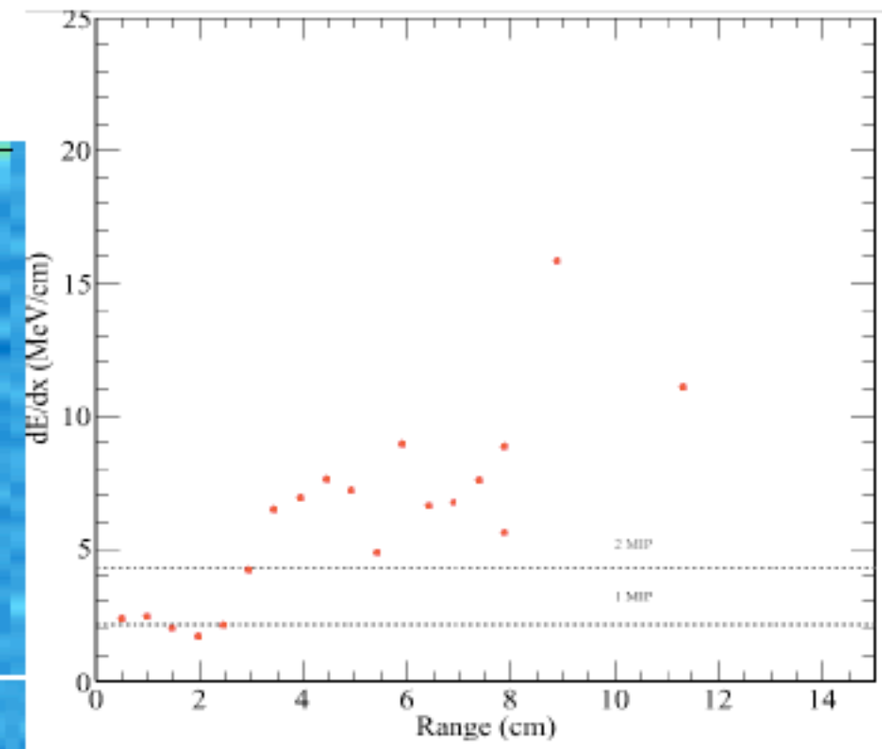
dE/dx shower separation

- Getting ready to measure with data.
- Resolving direction is more difficult with uncontained showers.
- In the process of selecting data sample.

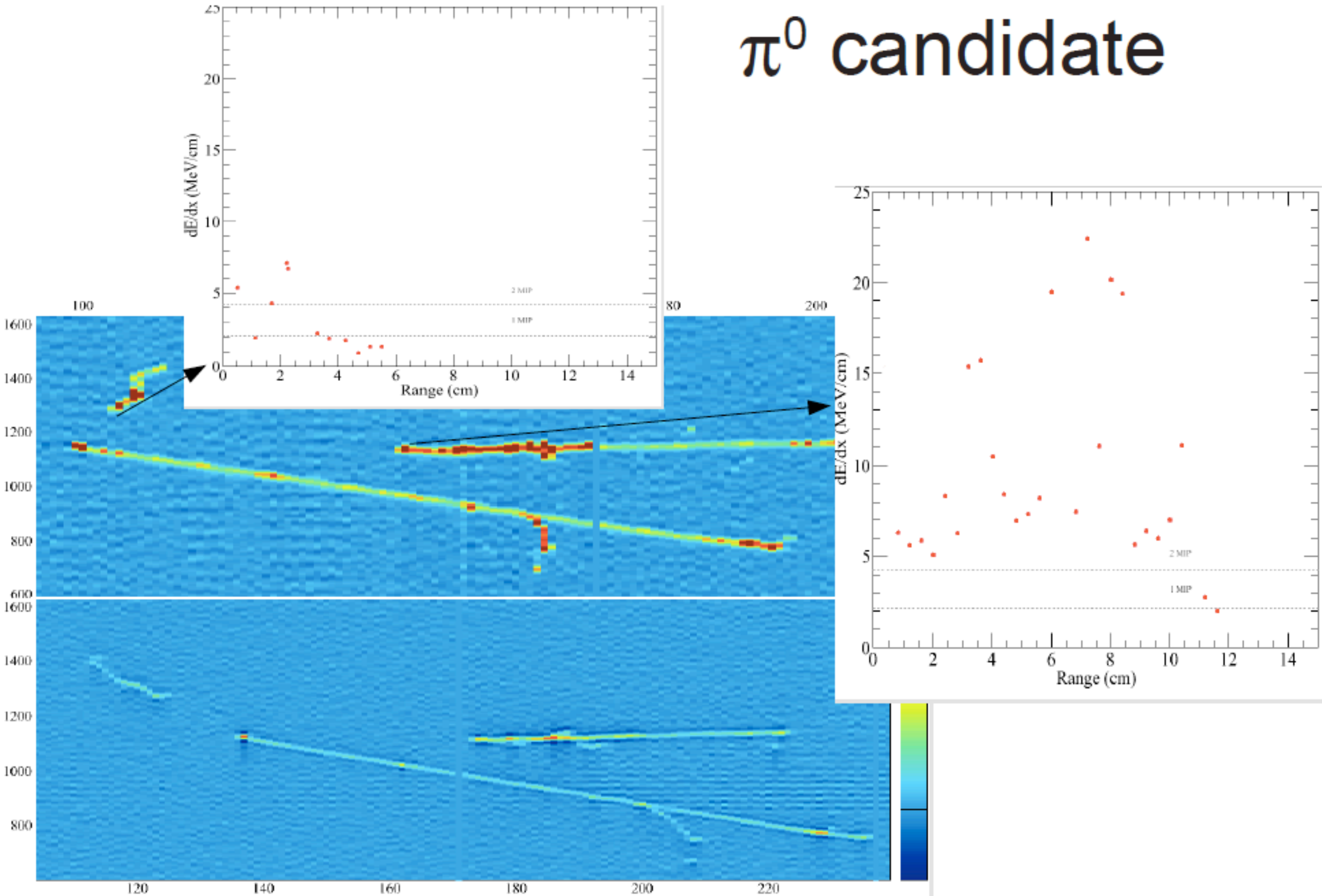


ν_e CC candidate

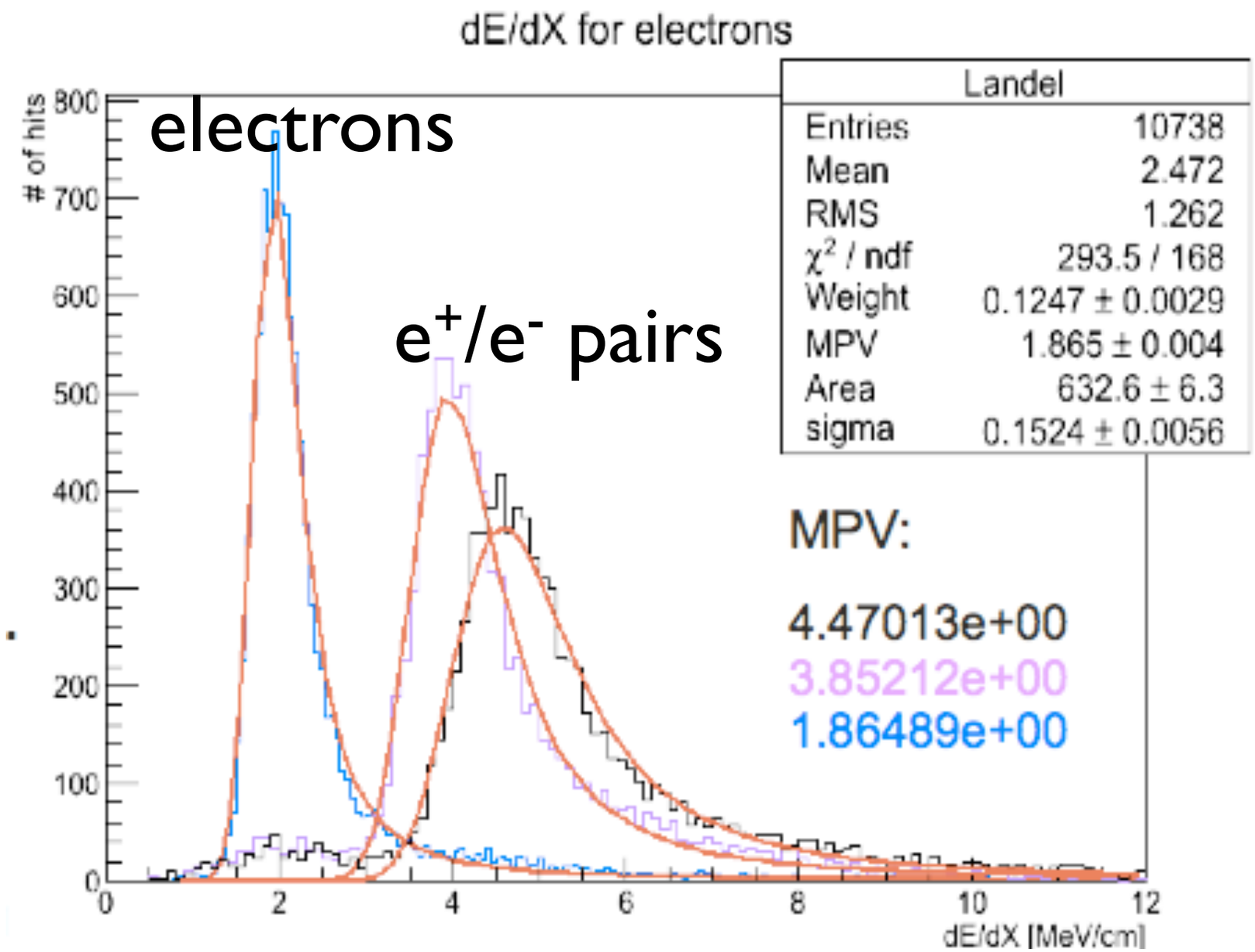




π^0 candidate



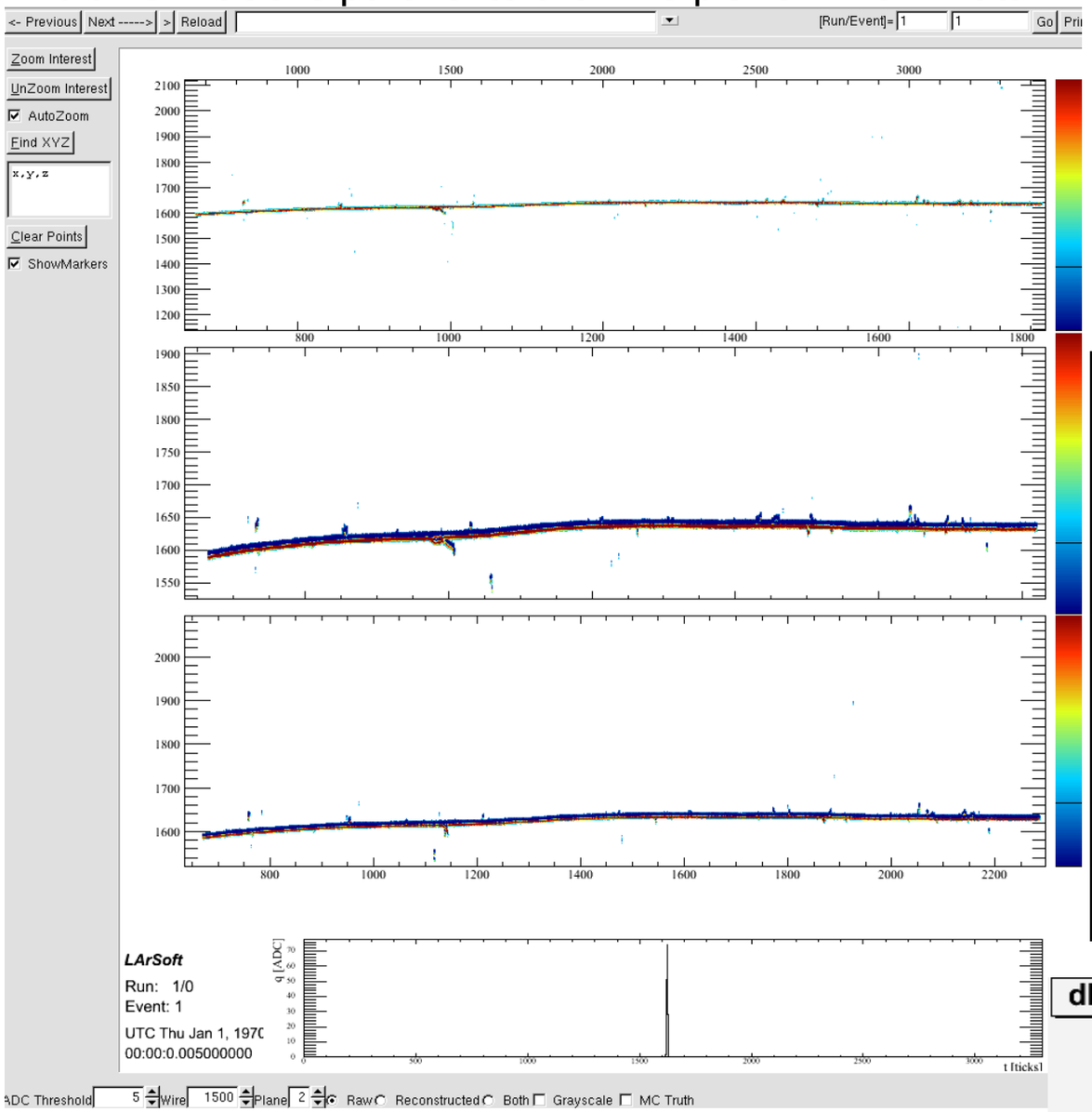
Shower energy reconstruction



A result of applying the Birks recombination effect. The tracks in argon are calculated separately and so the correction gets applied to each separately. But when they are read out the e-/e+ pair is read out together – larger ionization → larger correction

MC simulation

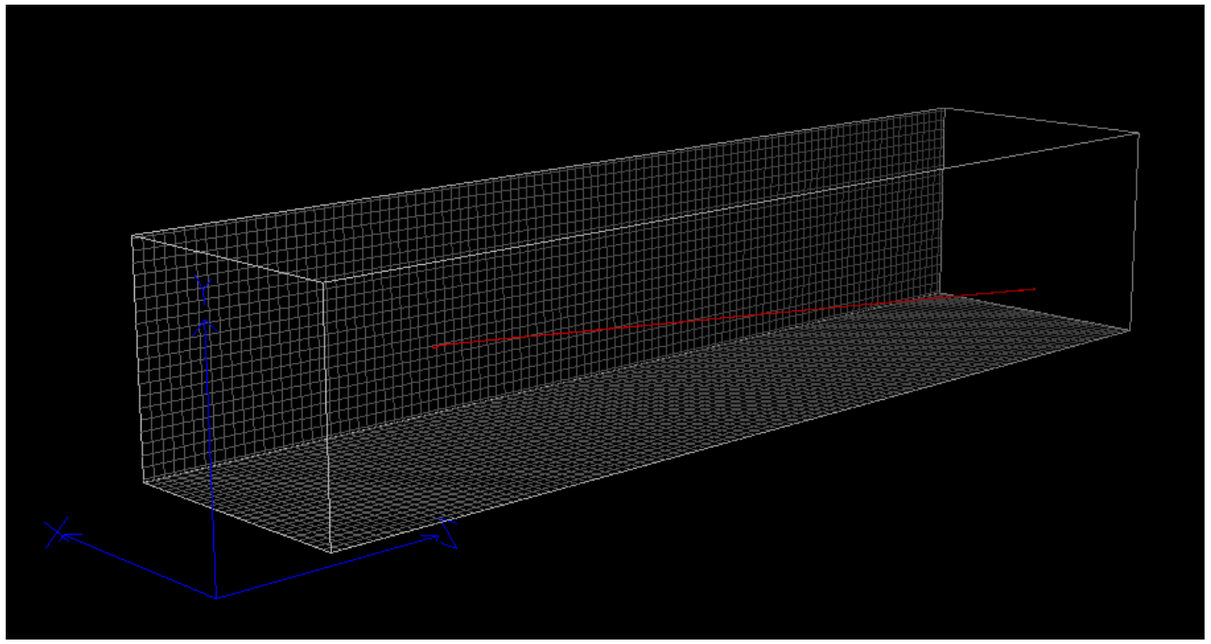
1)6 **GeV Muons** - tracks parallel to the wire plane - Raw Data



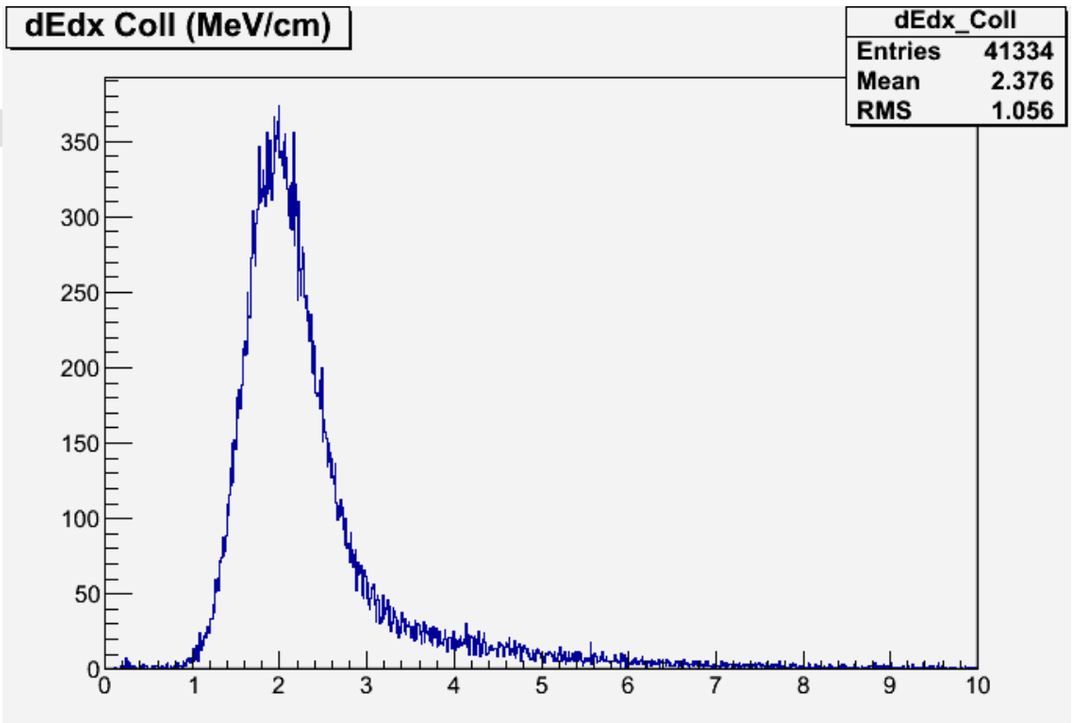
MicroBooNE calorimetric reconstruction

Coll:
~ 80 ADC

LArSoft tracking meeting
May 2 2012
Ornella

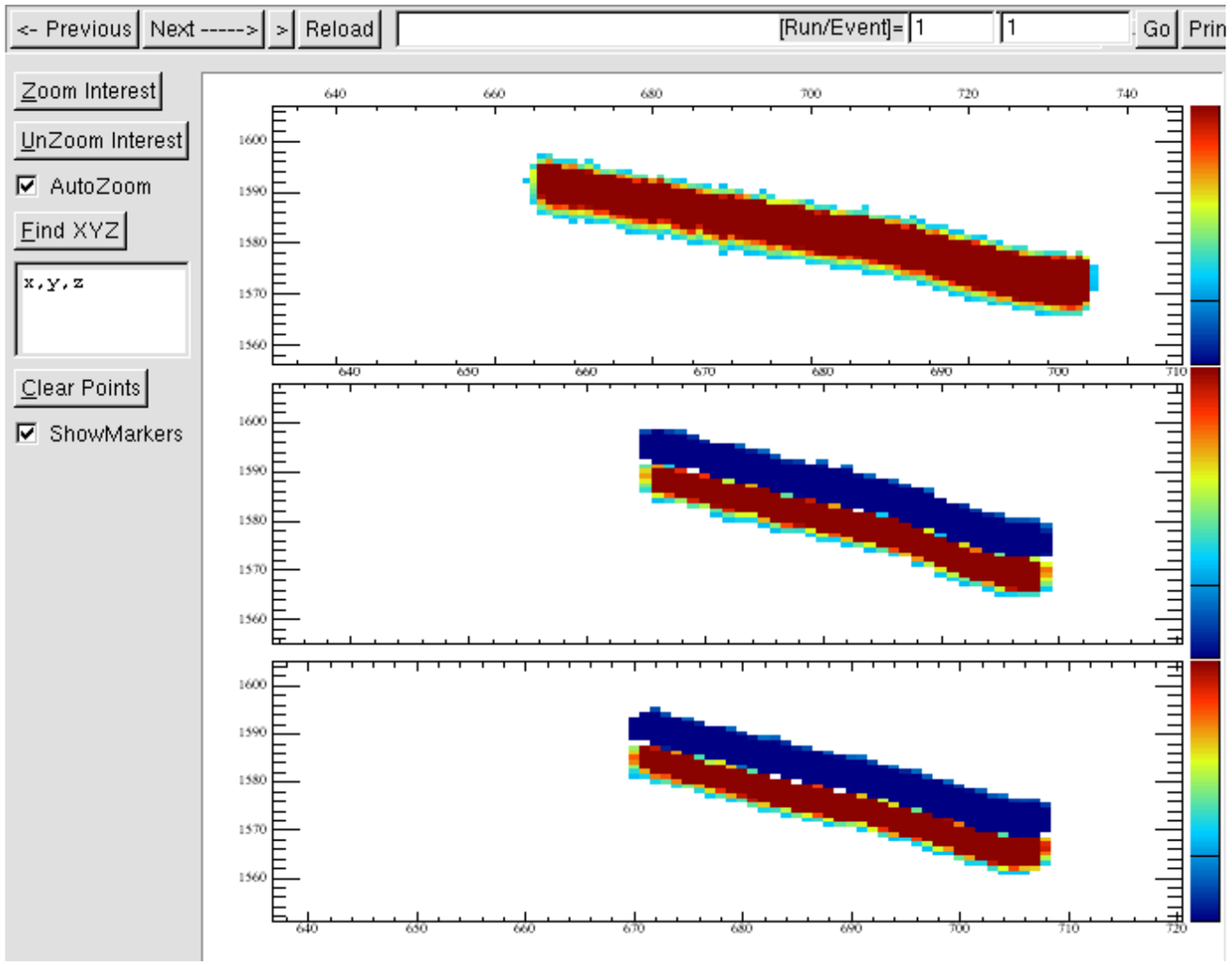


f_{cal}=43.008 ADC/fC
(as in LArsoft,
DetectorProperties in
Utilities)



2) **185 MeV protons** – Raw Data:

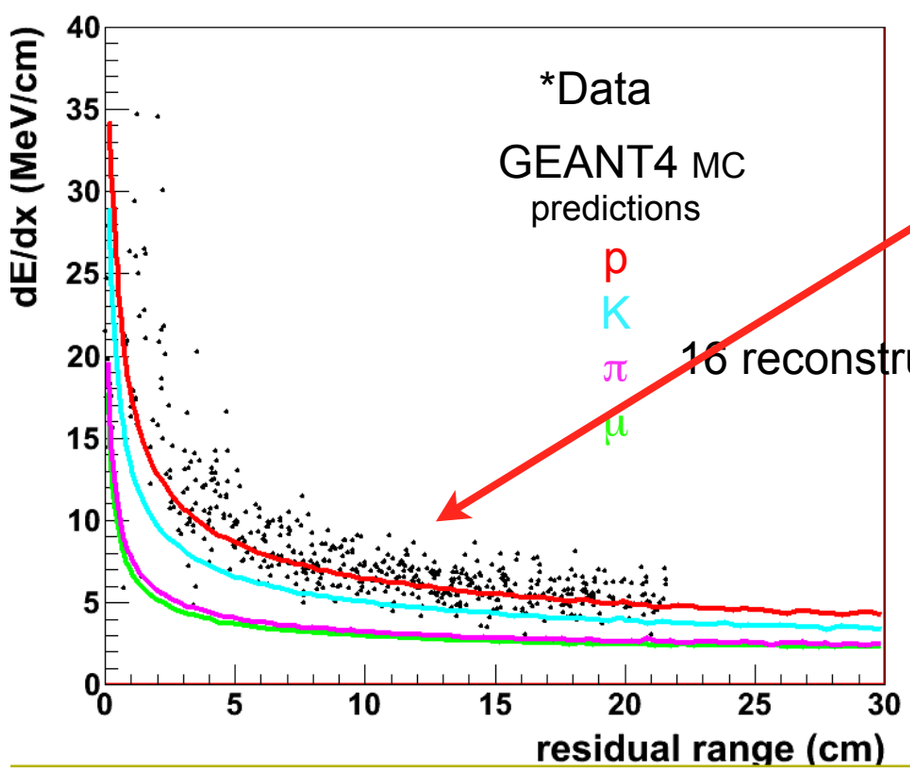
MicroBooNE calorimetric reconstruction



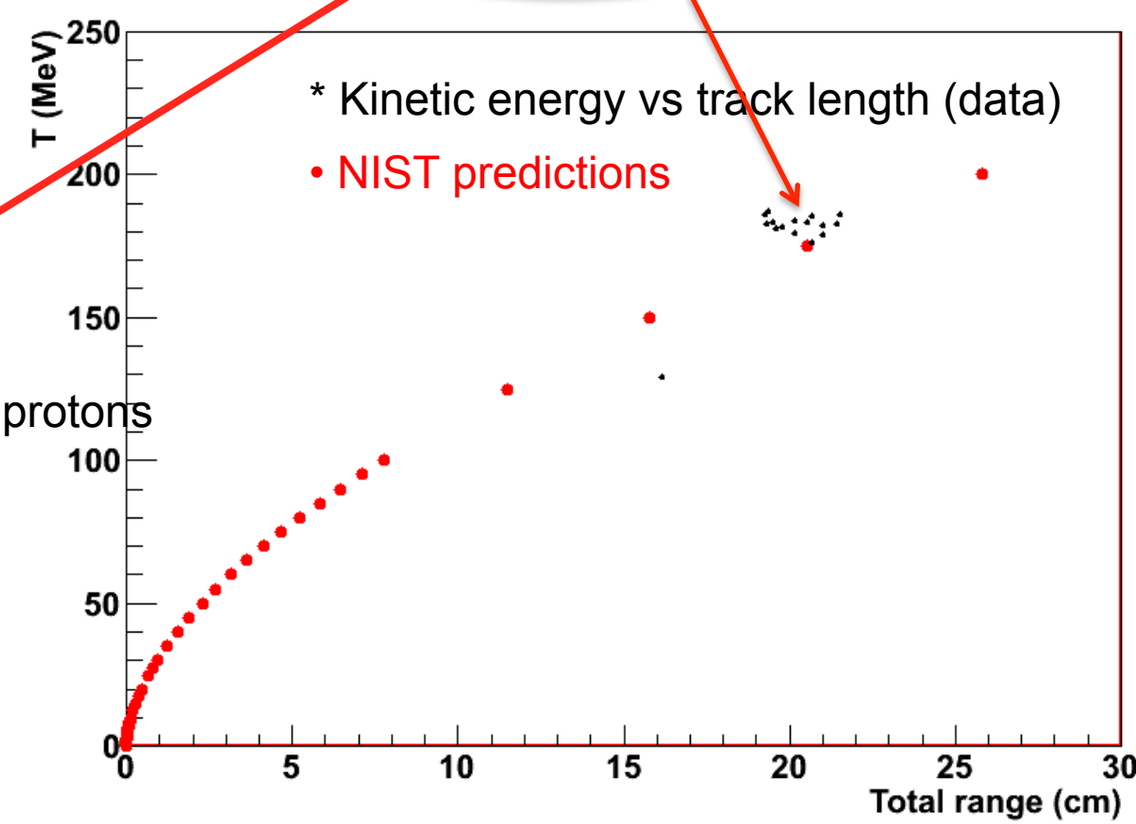
Coll:
~140 ADC beginning
~500 ADC end

LArSoft tracking meeting
May 2 2012
Ornella

Data-MC comparison:
f_{cal} a bit too large
or not good 3D reco?
To be investigated…



16 reconstructed protons



DATA-MC COMPARISON

- GENIE- Generates Events for Neutrino Interaction Experiments*

  FSI: Intranuclear Cascade mode (INC)

  Meson exchange (MEC) channel in the future

  GENIE 2.8.0

- GIBUU – The Giessen Boltzmann-Uehling-Uhlenbeck Project**

  FSI: Transport model

  2p2h-NN channel included

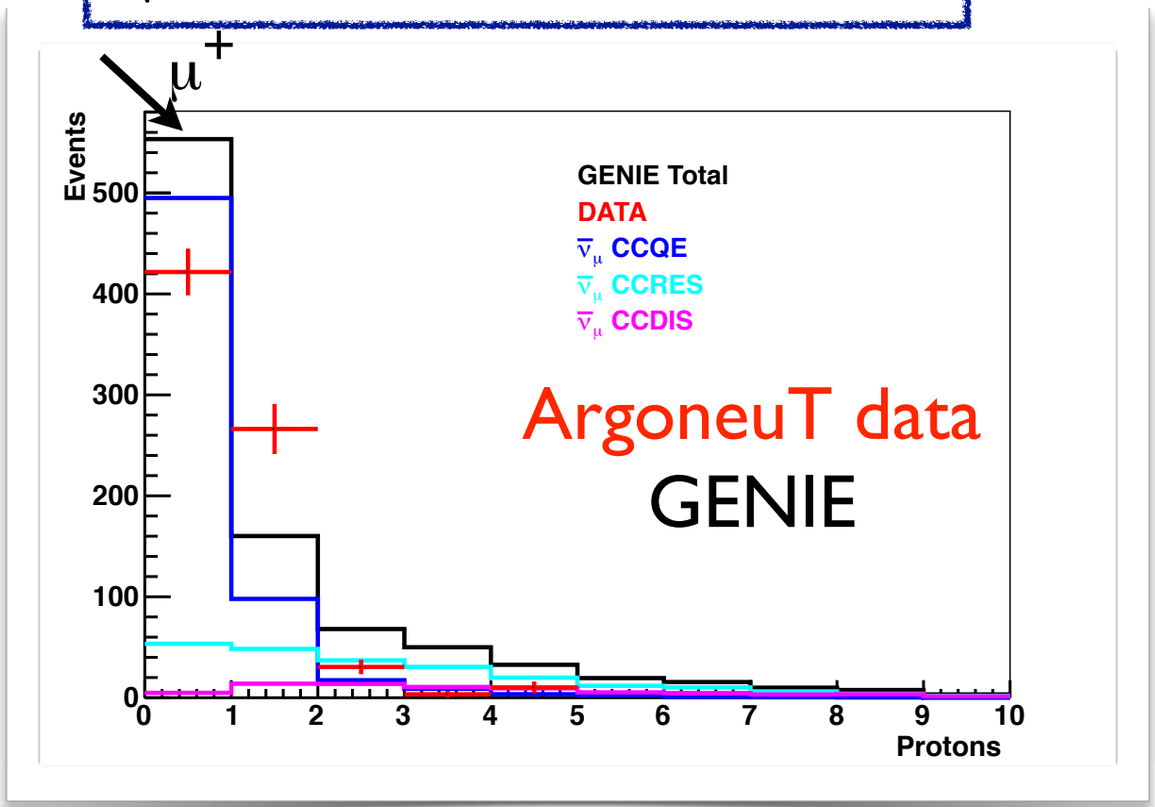
  2-particle-2-hole interaction with 2 nucleons produced

*ArgoNeuT Coll. is grateful to GENIE authors, in particular S. Dytman and H. Gallagher, for many useful discussions

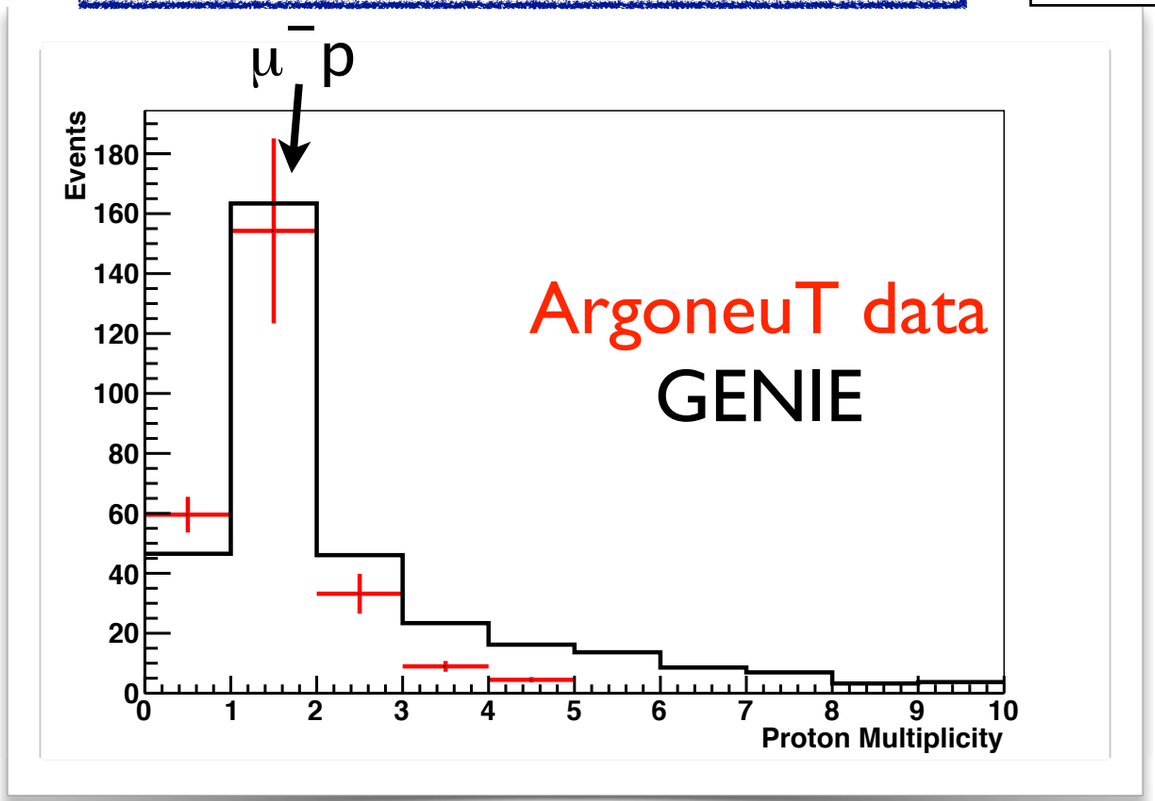
**ArgoNeuT Coll. is grateful to Olga Lalakulich and Ulrich Mosel for providing the GiBUU predictions and for many useful discussions

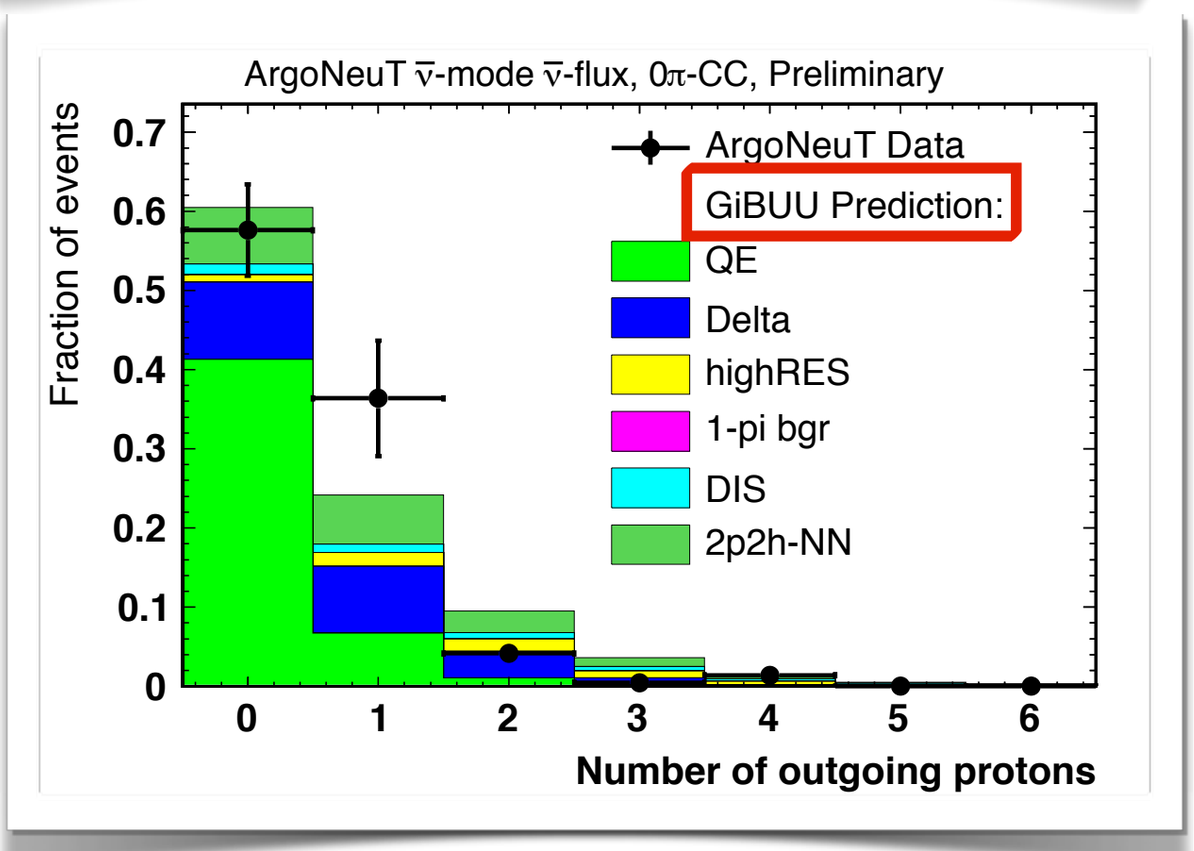
μ^+Np events PROTON MULTIPLICITY

$\bar{\nu}_\mu$ - anti-neutrino mode run



ν_μ - anti-neutrino mode run



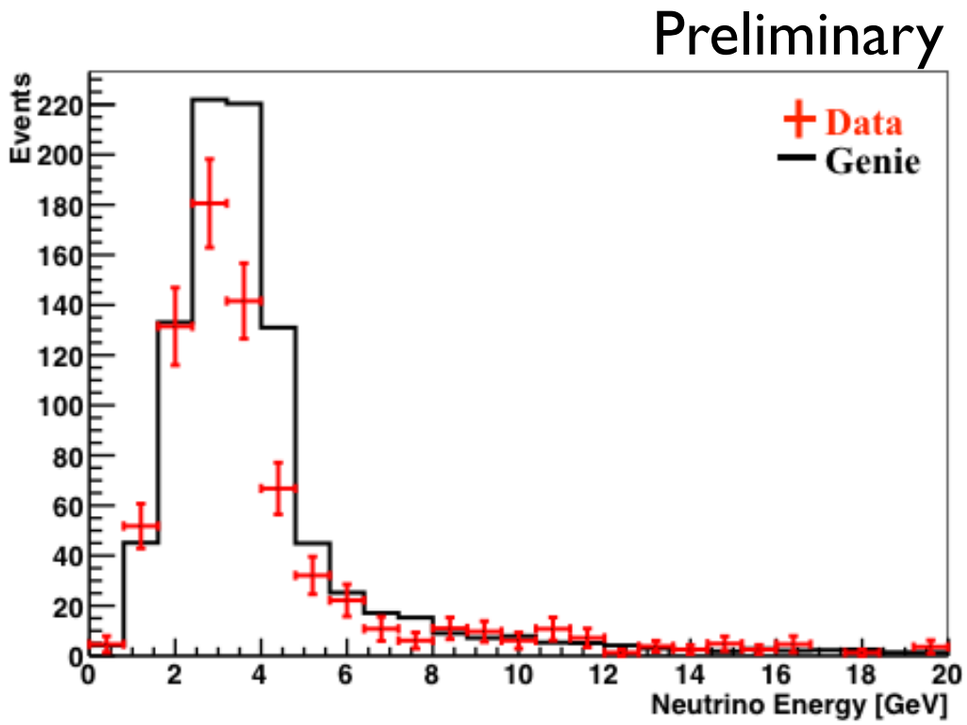


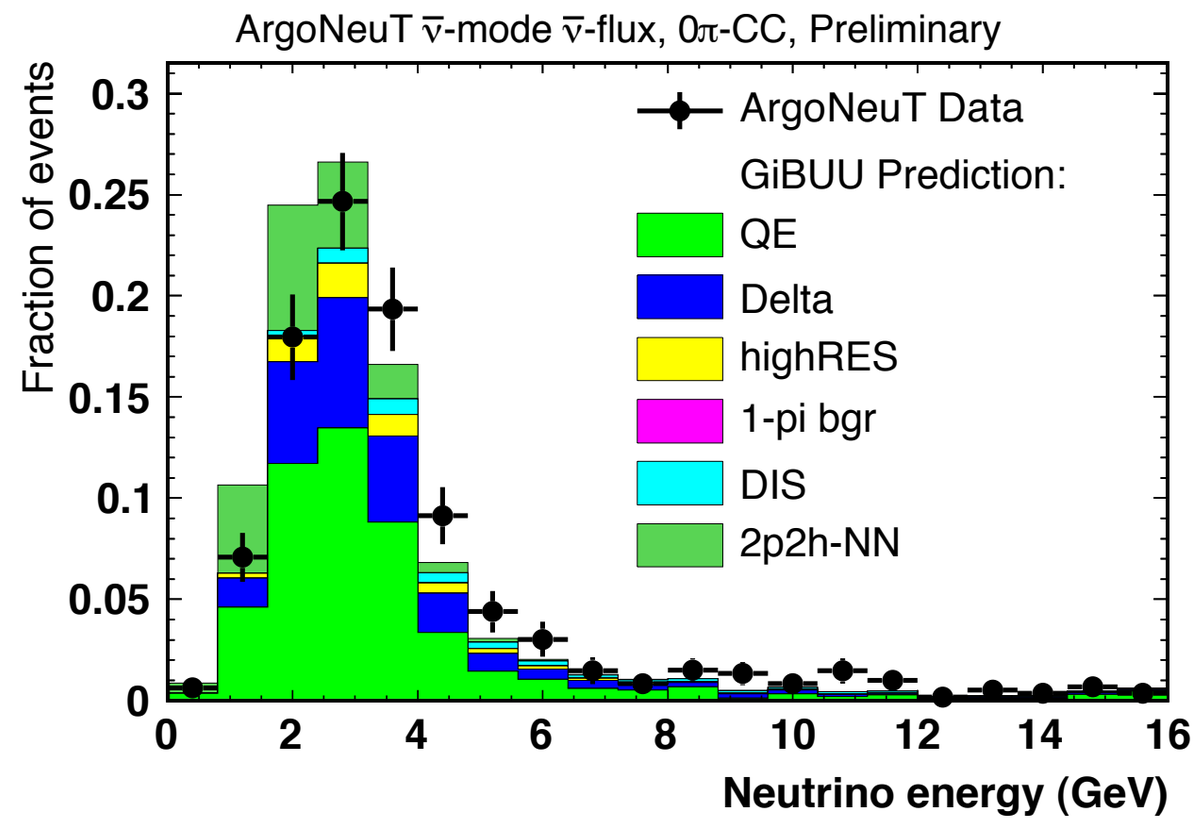
- Ratios among rates of different proton multiplicities in DATA don't agree with MC, in particular for $\bar{\nu}_\mu$
- ~30% contribution from not CCQE events (FSI)

•Uncertainties on the neutrino flux not yet included. Improved flux tuning to be used
•Efficiency for the selection of high multiplicity events not (yet) optimized
•Studies of background effects are ongoing and will be finalized soon

$\bar{\nu}_\mu$ - anti-neutrino mode run

Neutrino energy (1μ+Np)





$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

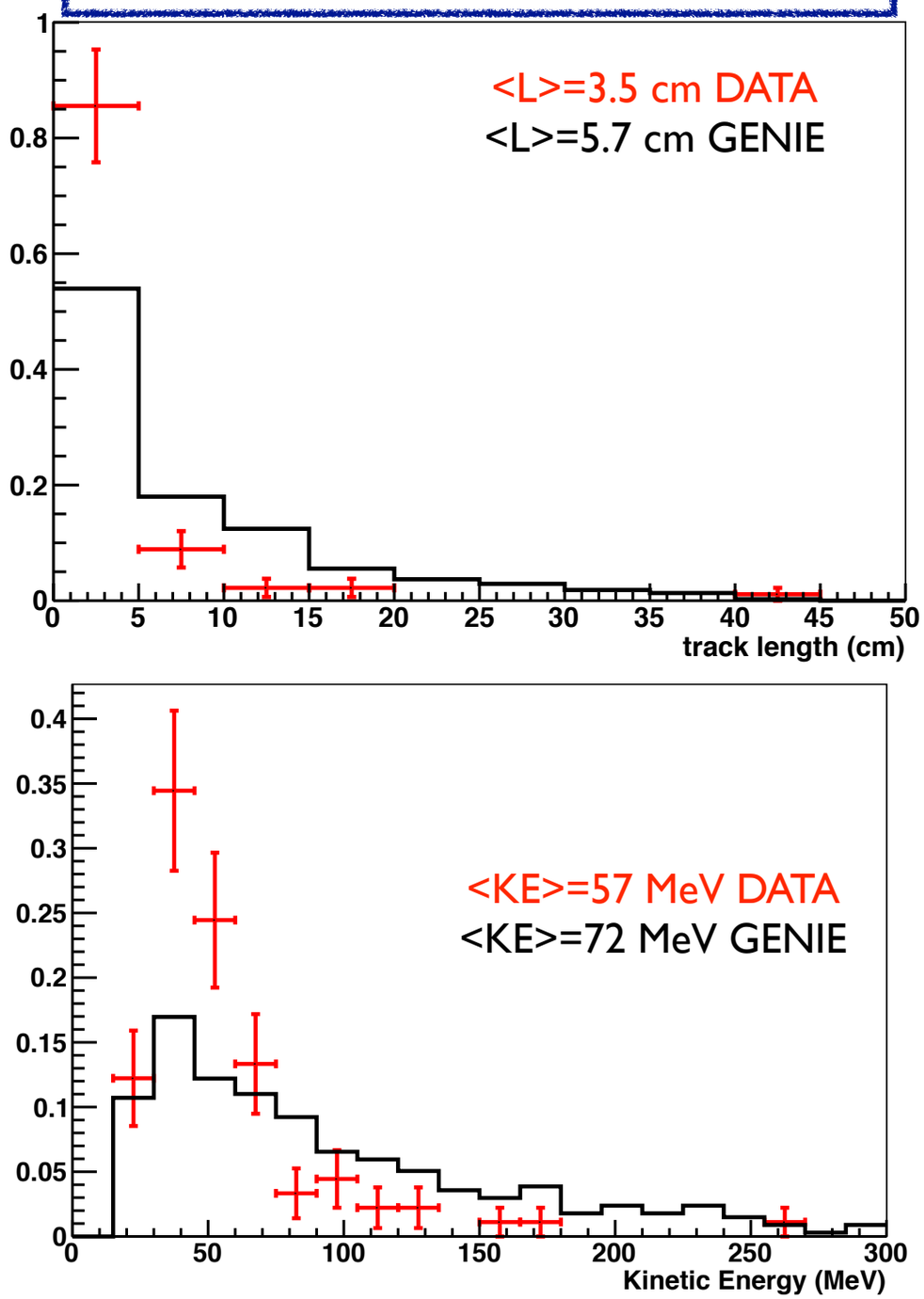
- Data energy reconstructed with the QE formula.
- Improved energy reconstruction including proton kinematics in progress(see later)

μ^+/μ^- p events

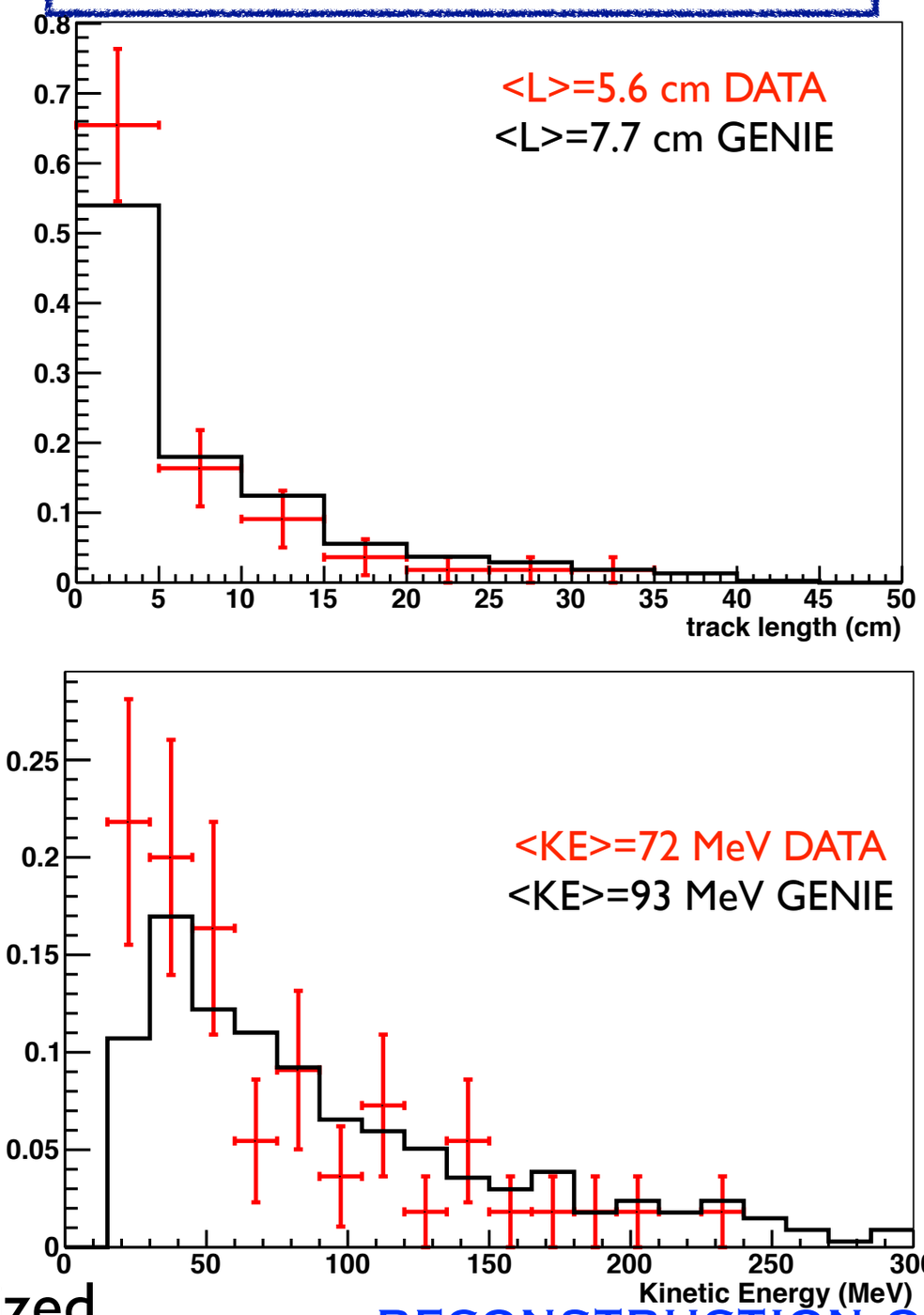
PROTON KINEMATICS

(Event-by-event proton reconstruction)

$\bar{\nu}_\mu$ - anti-neutrino mode run



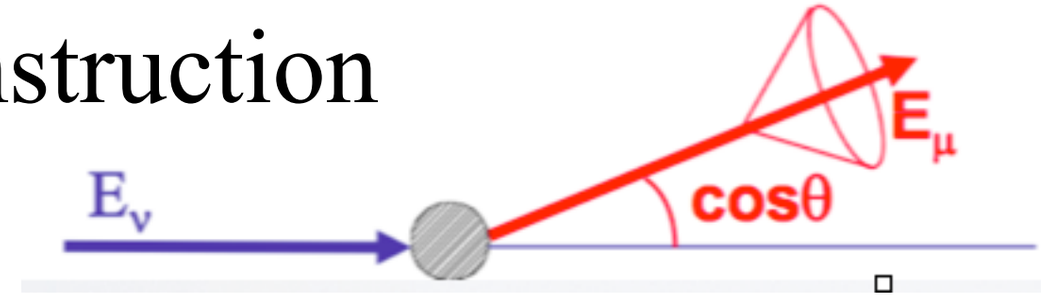
ν_μ - anti-neutrino mode run



area normalized
comparison inside the detector

RECONSTRUCTION OF PROTON KINEMATICS IN ALL CC 0 PION EVENTS

Neutrino Energy Reconstruction



1)

$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

μ kinematics

automatic reconstruction

$$p_h = \sqrt{(E_\nu - p_\mu cos\theta_\mu)^2 + p_\mu^2 sin^2\theta_\mu}$$

$$cos\theta_h = (E_\nu - p_\mu cos\theta_\mu)/p_h$$

assumes QE events! and interaction on a nucleon AT REST

predicted proton angle and momentum

2)

$$E_\nu = p_\mu \cos\theta_\mu + p_p \cos\theta_p$$

NOMAD

μ + p kinematics (p_p and θ_p)

semi-automatic reconstruction

3)

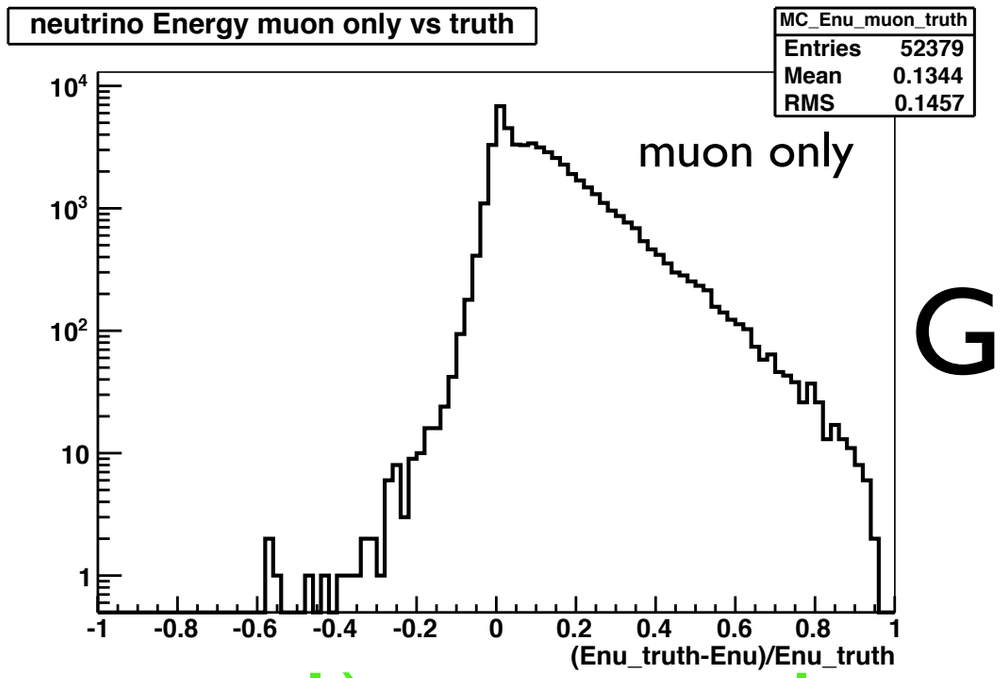
$$E_\nu = E_\mu + T_p$$

Energy conservation

μ + p kinematics (p_p and θ_p)

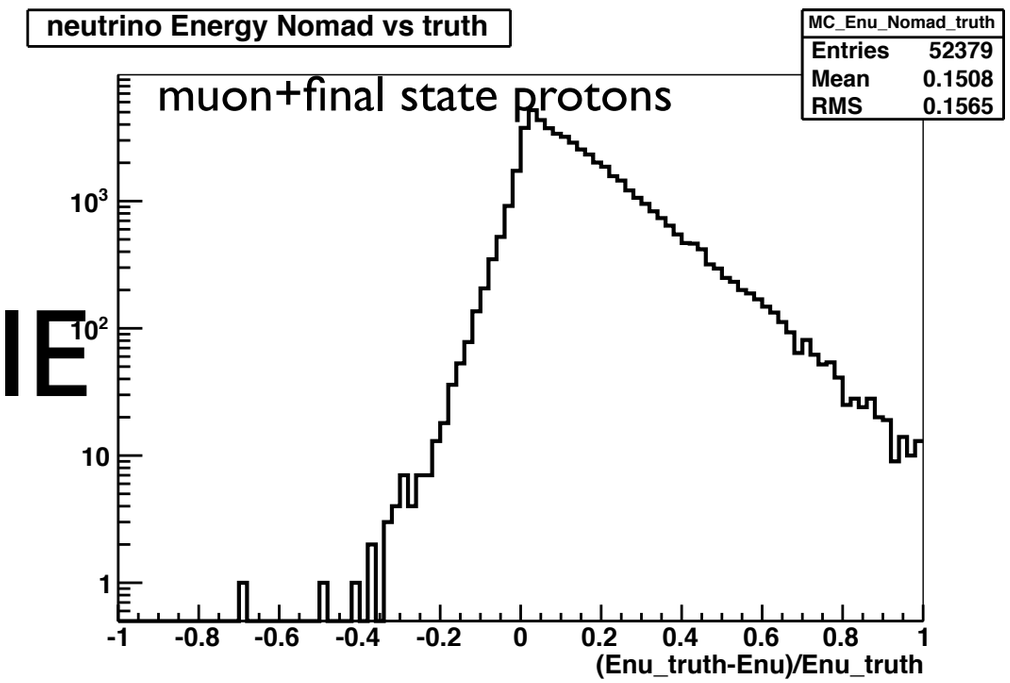
semi-automatic reconstruction

Energy reconstruction: (Enu_truth-Enu_reco)/Enu_truth

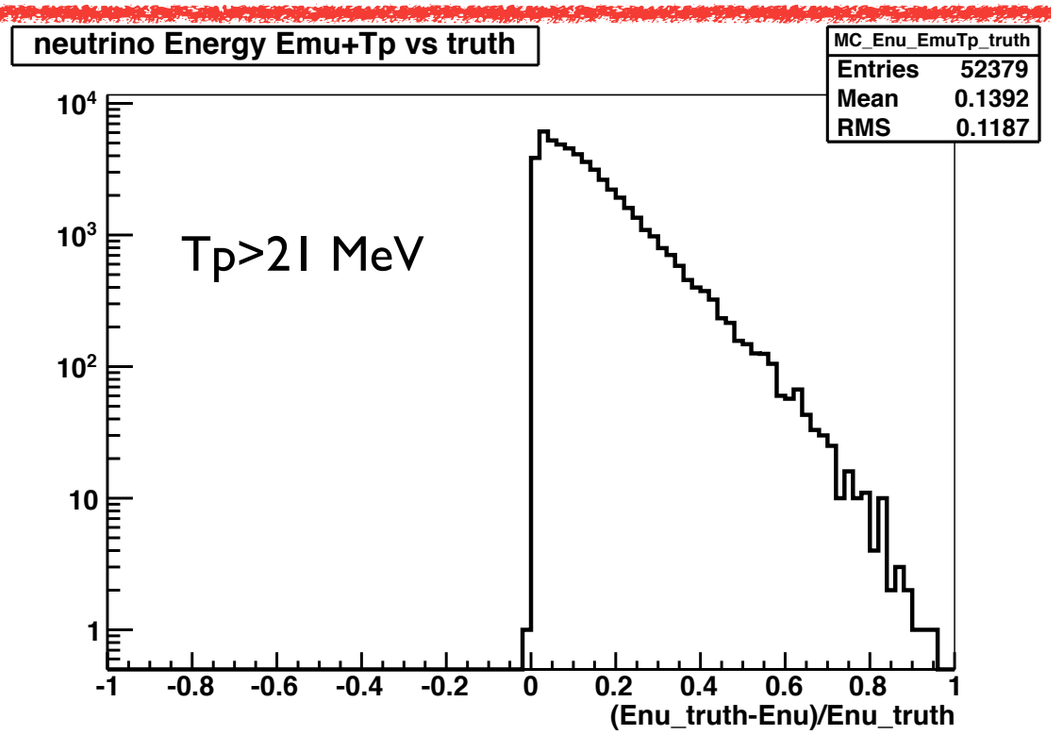


1) muon only

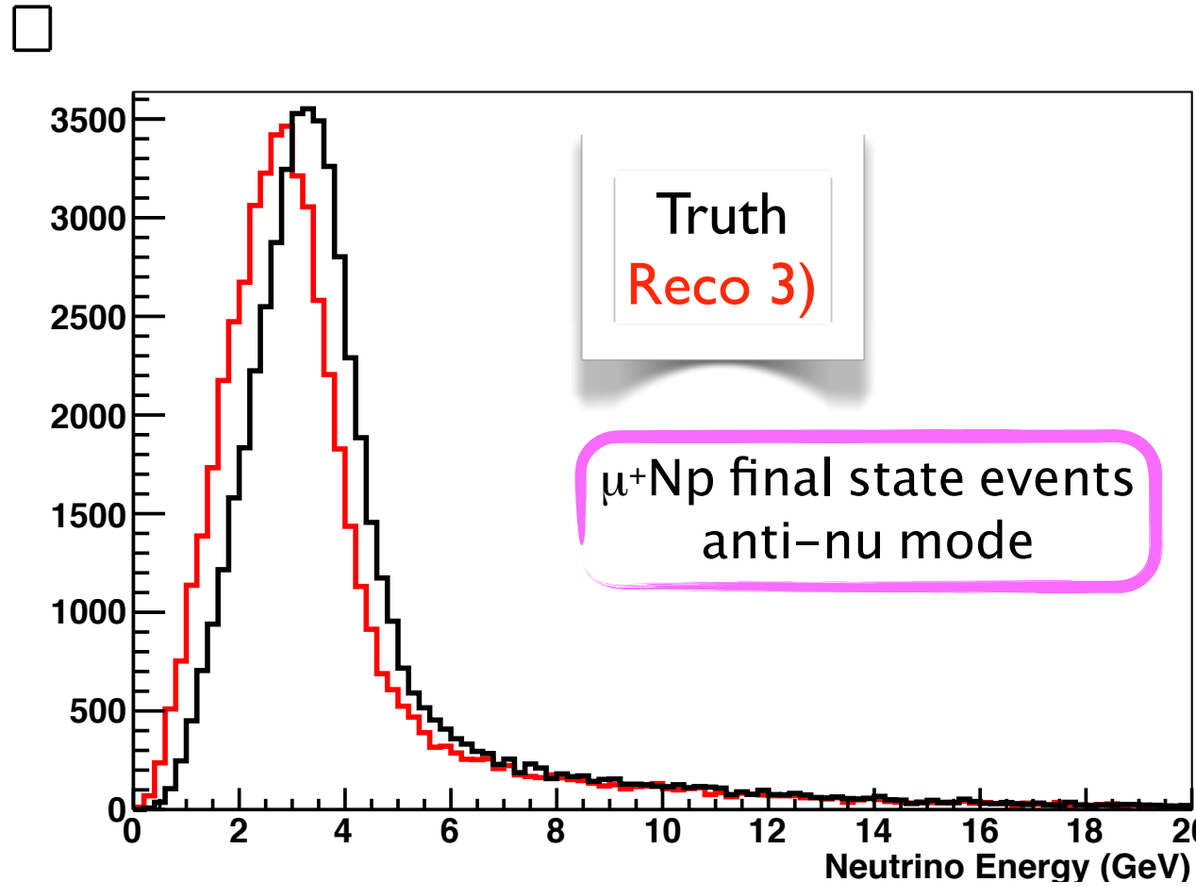
GENIE



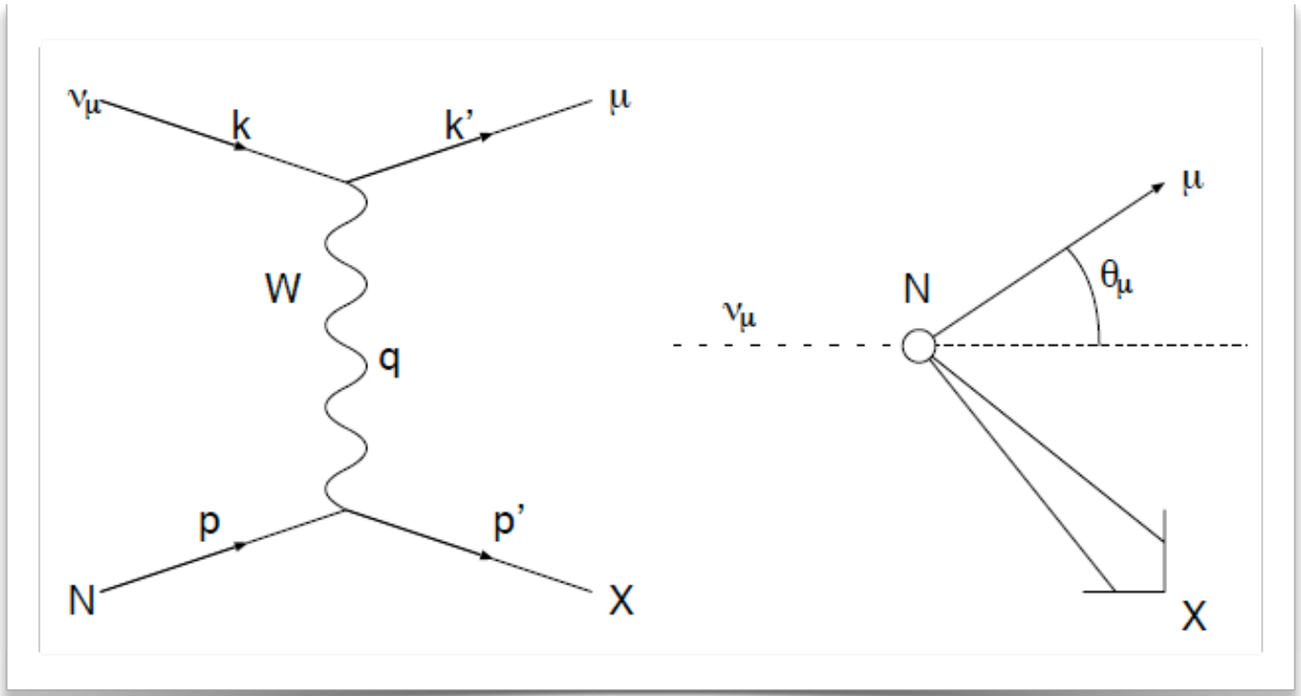
2) Nomad



3) Energy conservation



RECONSTRUCTED KINEMATICAL VARIABLES
(*FROM MUON* **AND** *PROTON KINEMATICS*)



T_p=measured proton kinetic energy

Neutrino Energy $E_\nu = E_\mu + E_{had}$, $E_{had}=\sum T_p$

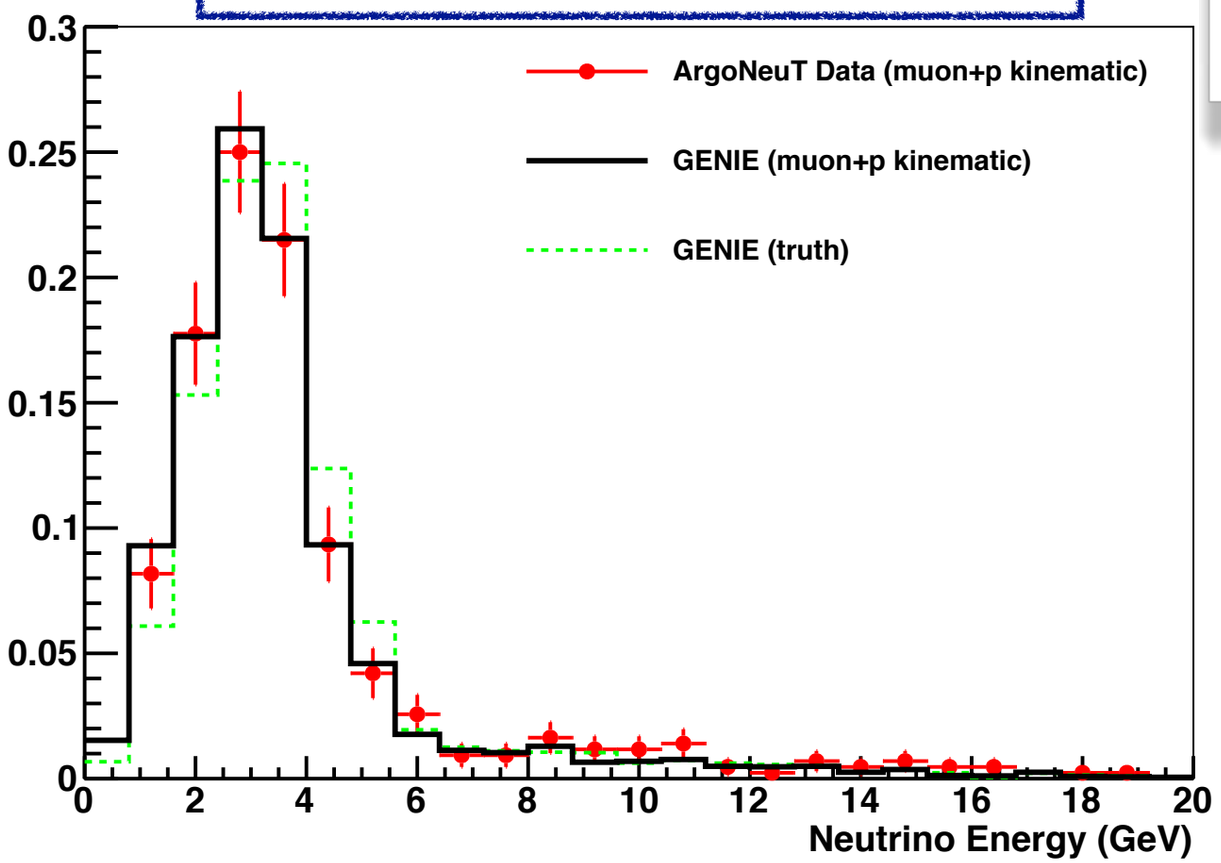
$\nu = E_\nu - E_\mu$ inelasticity, $y = \frac{q \cdot p}{k \cdot p}$ $\quad y = \frac{E_{had}}{E_\nu}$,

squared four-momentum transfer, $Q^2 = -q \cdot q$ $\quad Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$

the Bjorken scaling variable, $x = \frac{Q^2}{2q \cdot p}$, $\quad x = \frac{Q^2}{2M_N E_{had}}$,

NEUTRINO ENERGY RECONSTRUCTION
(*FROM MUON* **AND** *PROTON KINEMATICS*)

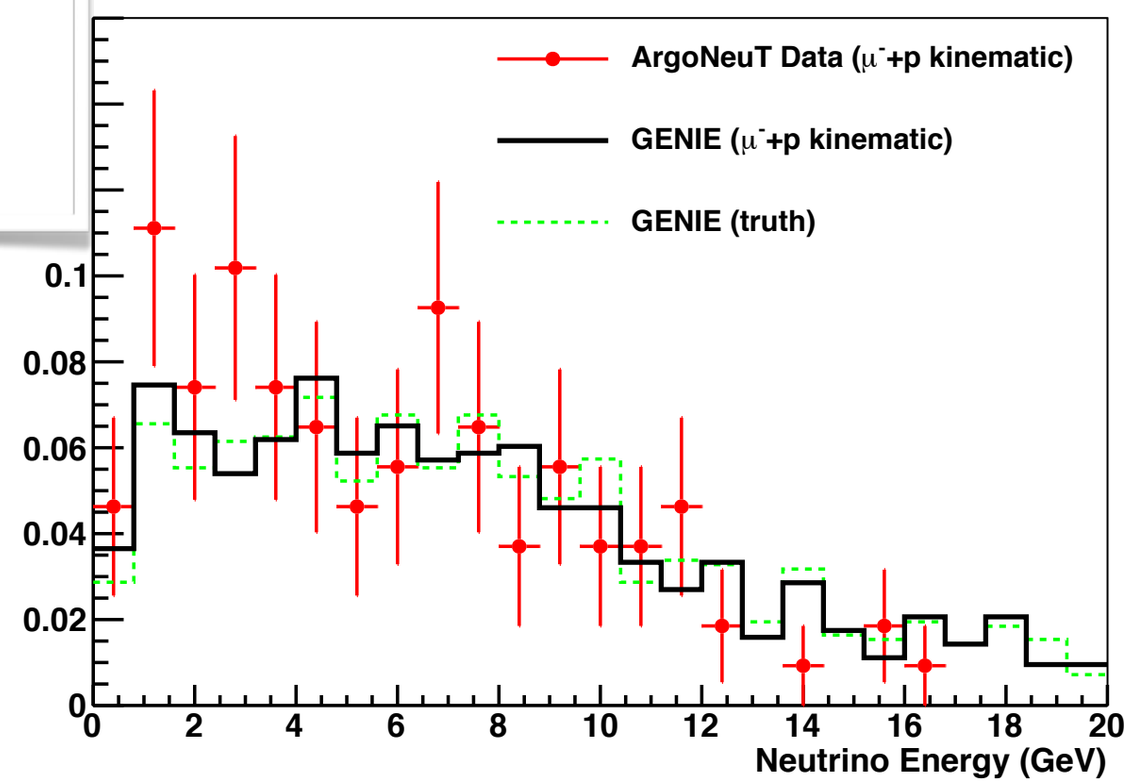
$\bar{\nu}_\mu$ - anti-neutrino mode run



Including hadronic vertex reconstruction
No model dependence

Area normalized comparison

ν_μ - anti-neutrino mode run



DATA-MC COMPARISONS
WITH MC OF
(ν, Q^2, y, x_B...)
DISTRIBUTIONS
IN PROGRESS

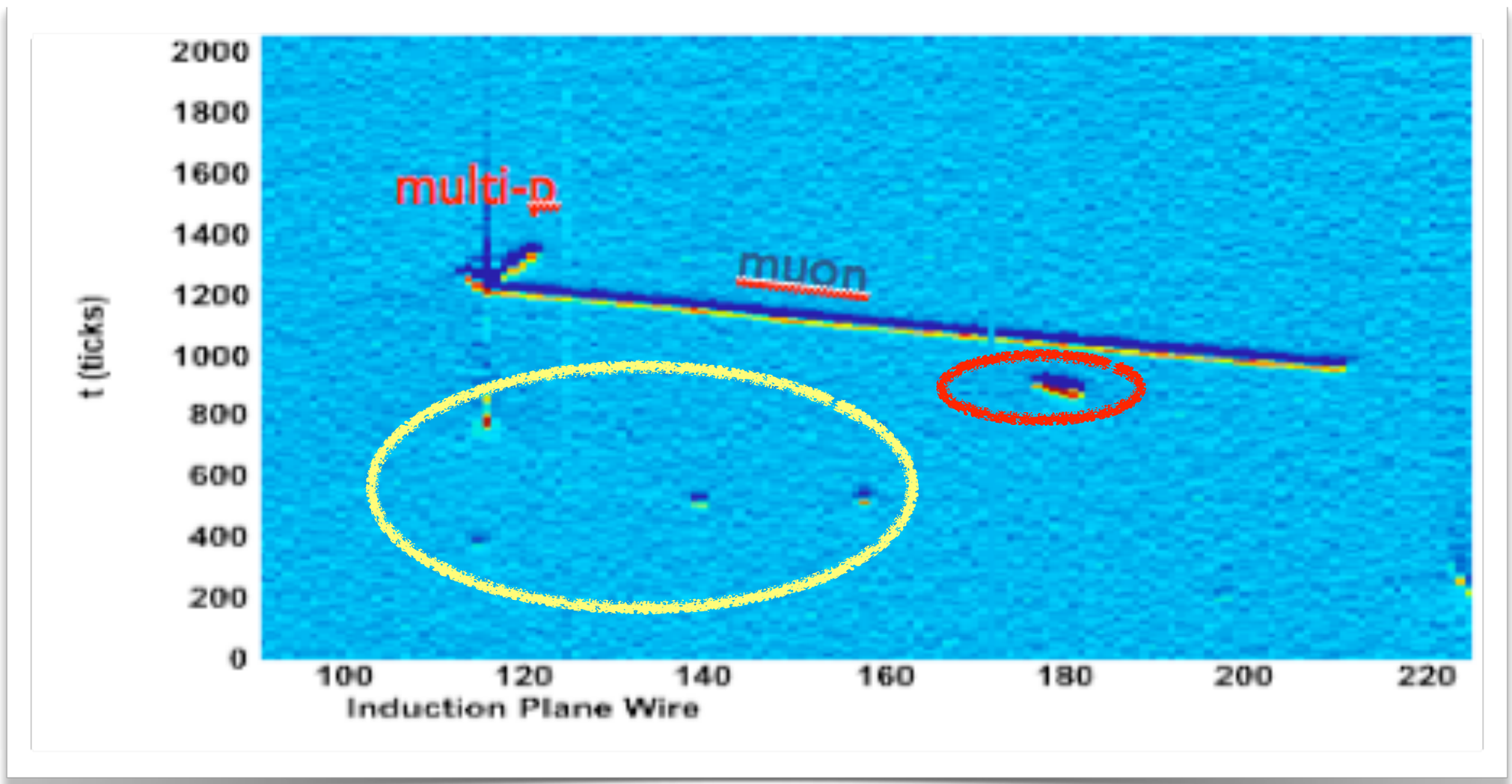
ArgoNeuT

VERTEX ACTIVITY

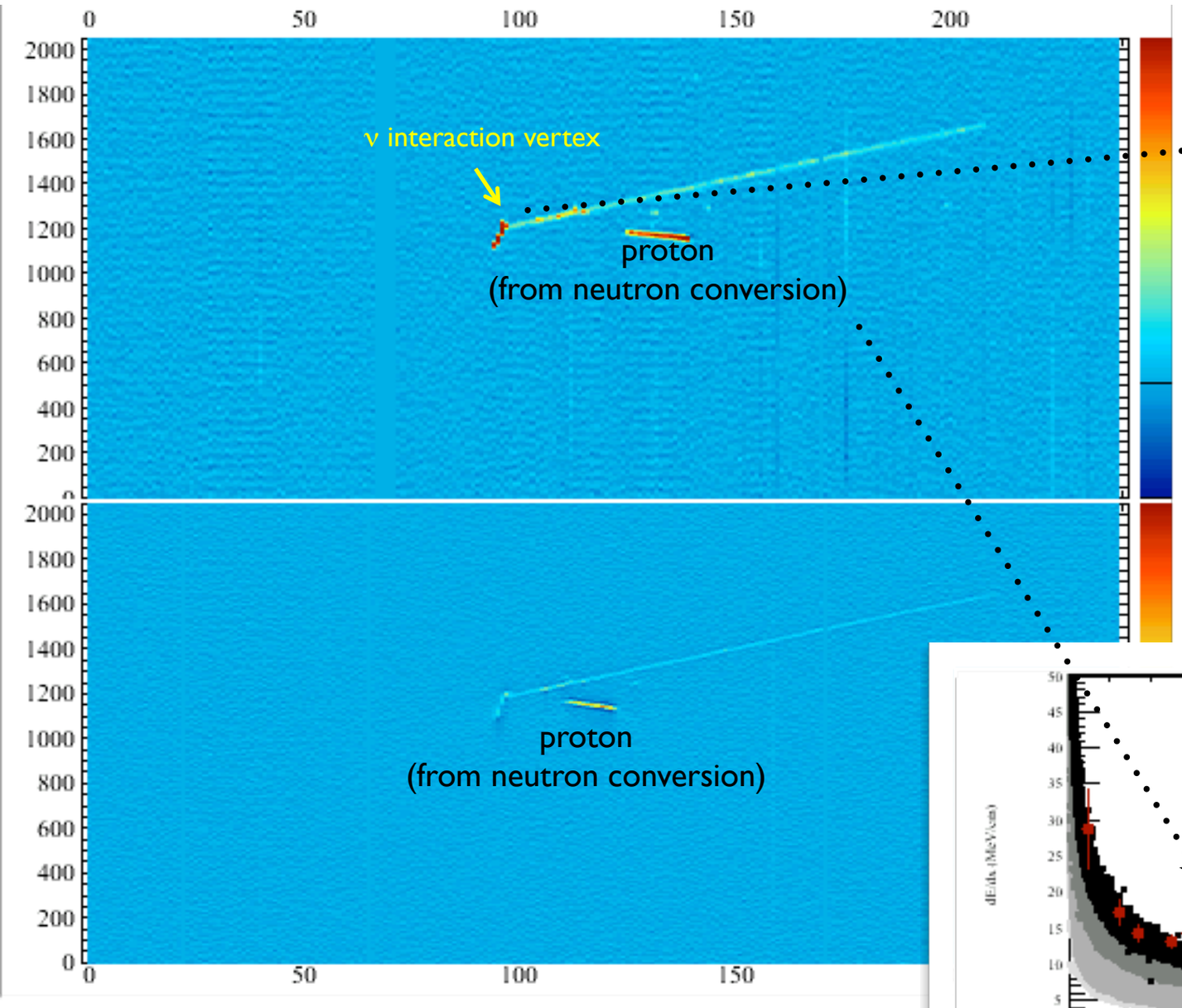
Analysis in progress

Measurement of γ activity around the vertex and neutron → proton can also help to tune MC generators

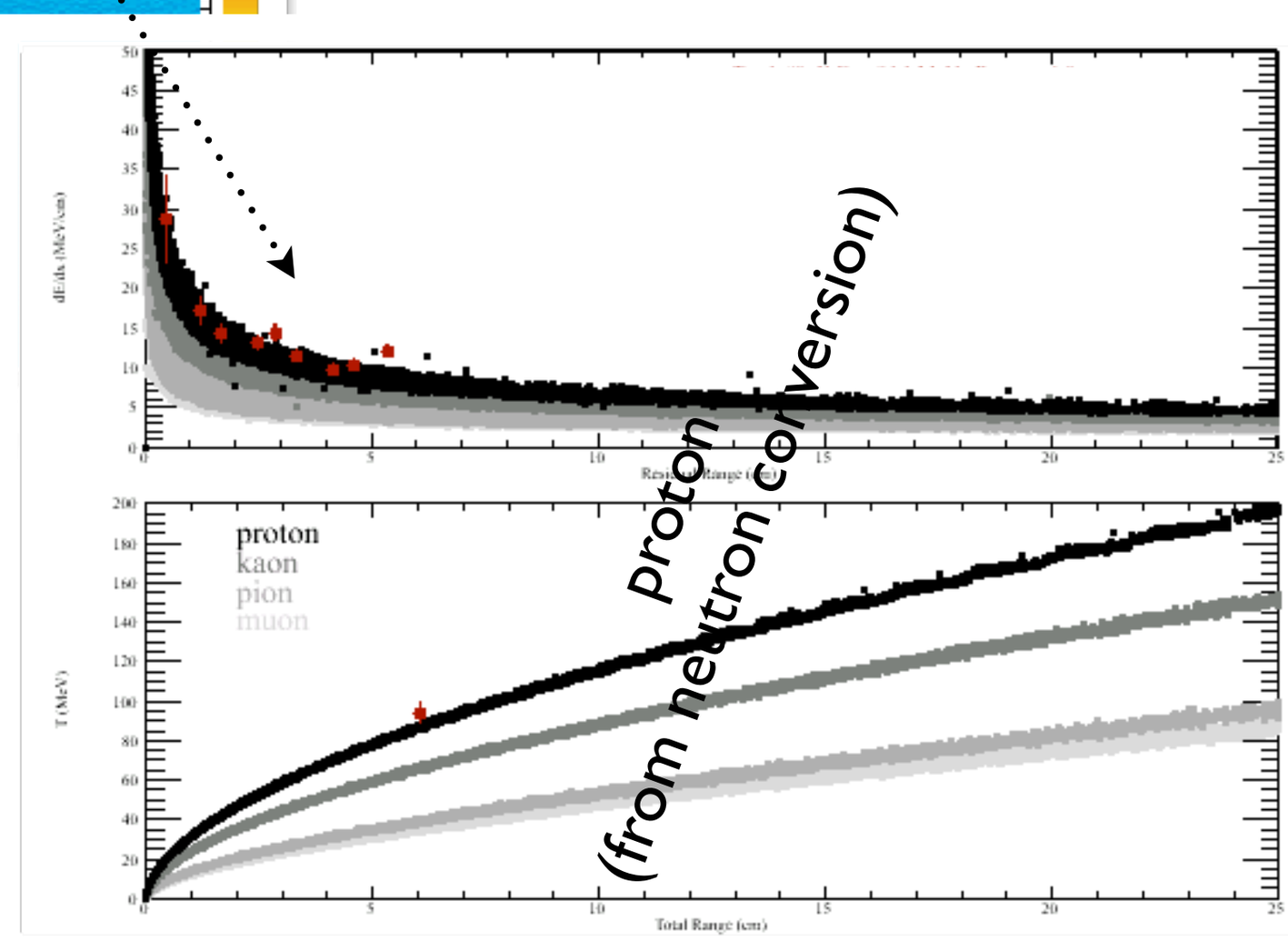
short heavily ionizing track(s)
(ie. mainly proton track emitted from n interaction on Ar nuclei)
detached from the vertex



Reconstruction of proton from neutron conversion

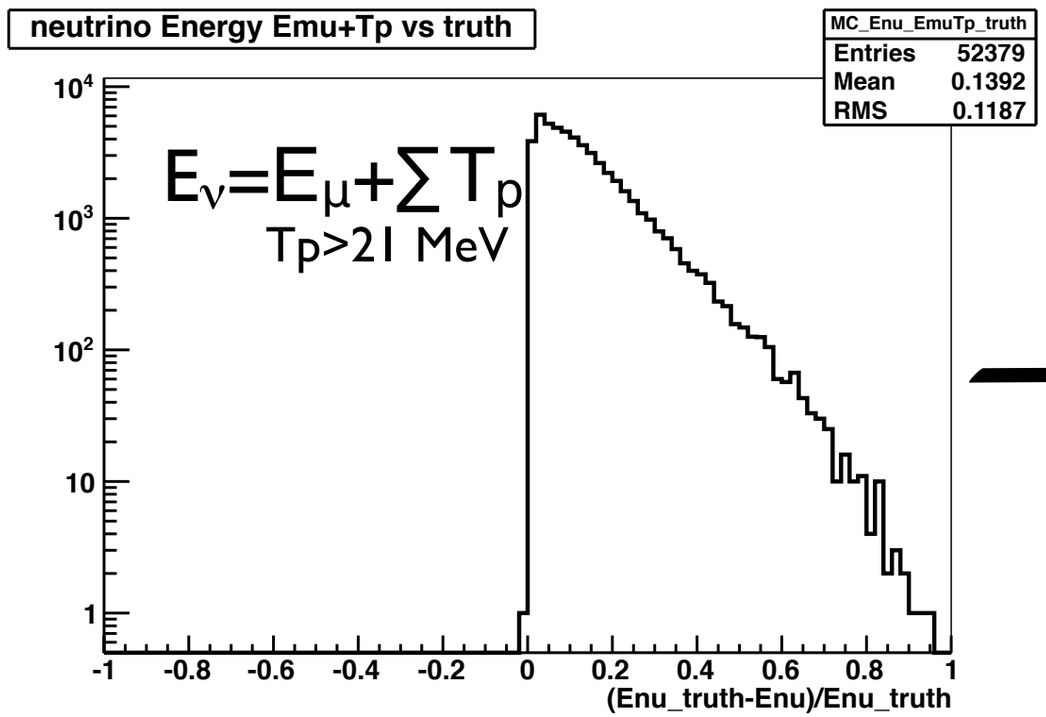


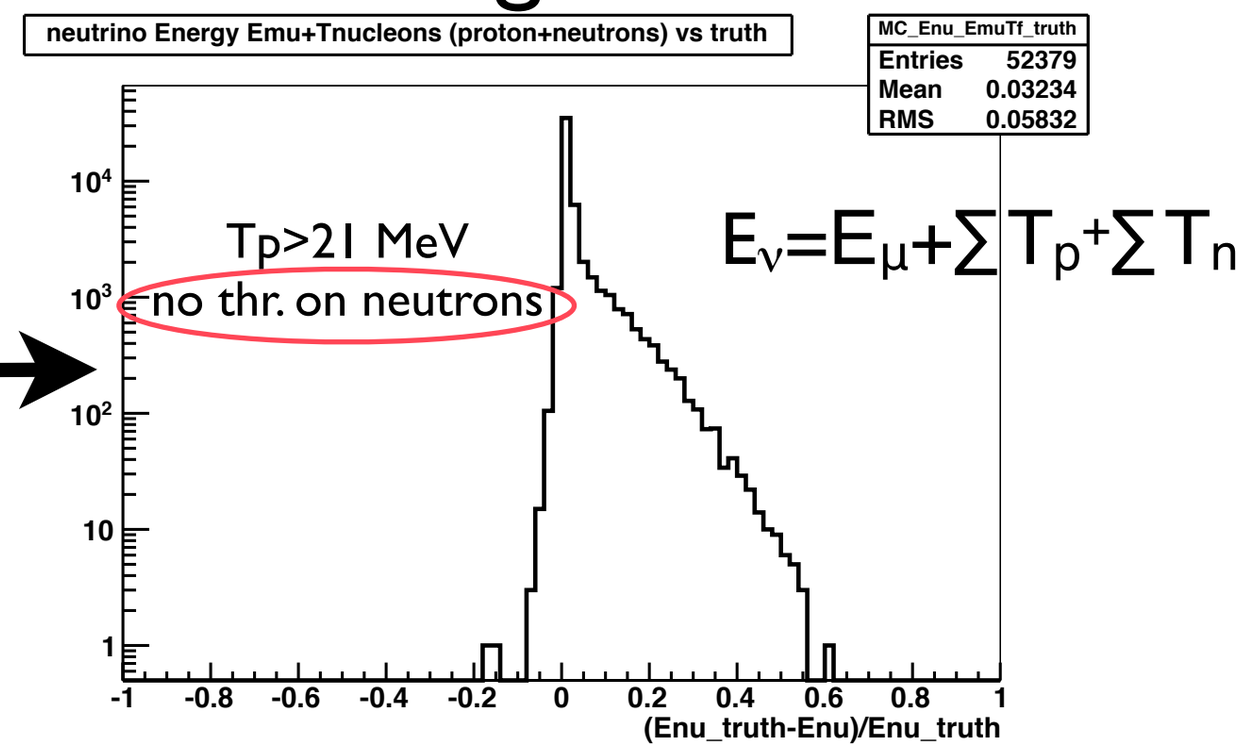
proton at the vertex:
trk_length=2.91 cm, KE=39.5 MeV

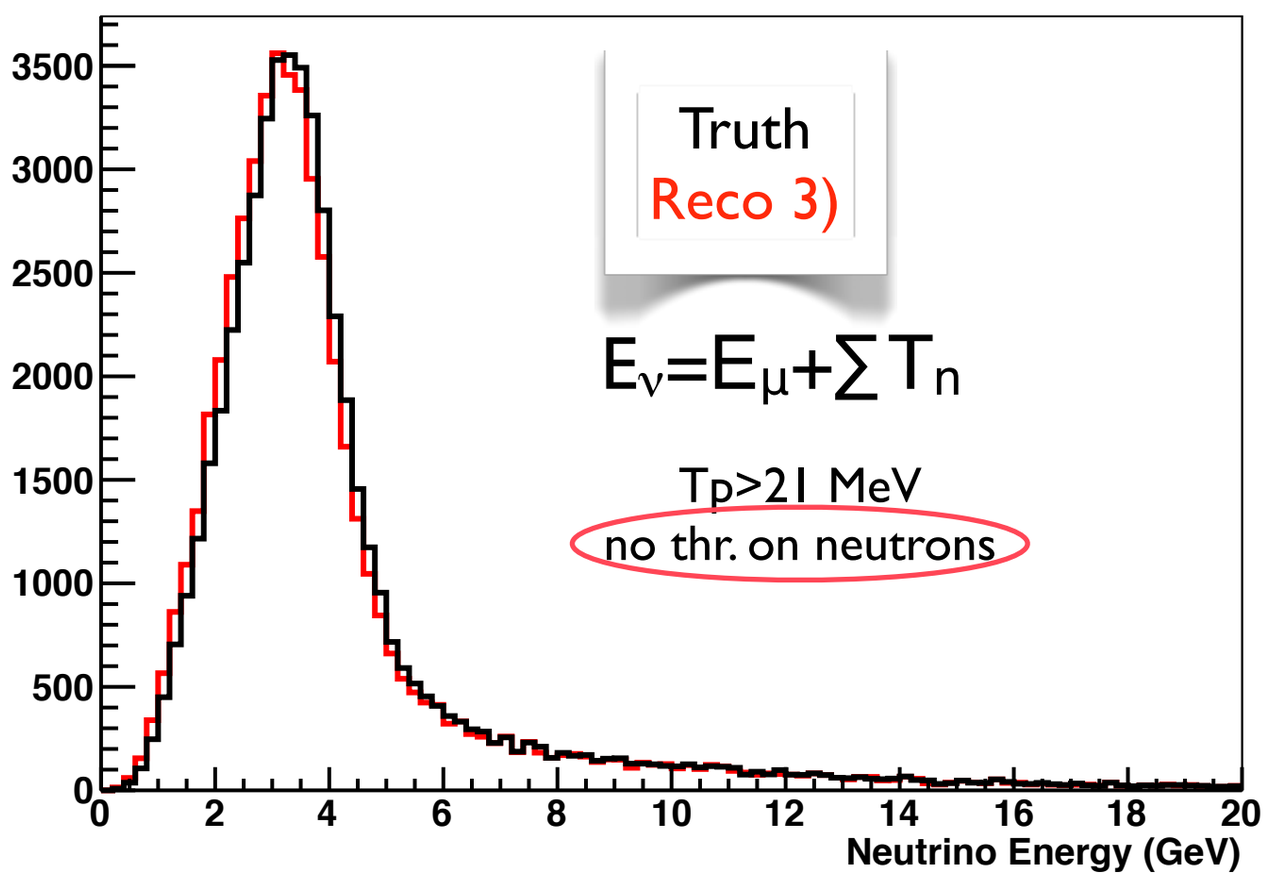


Few events with n->p in ArgoNeuT
(too small volume)

Including neutrons...







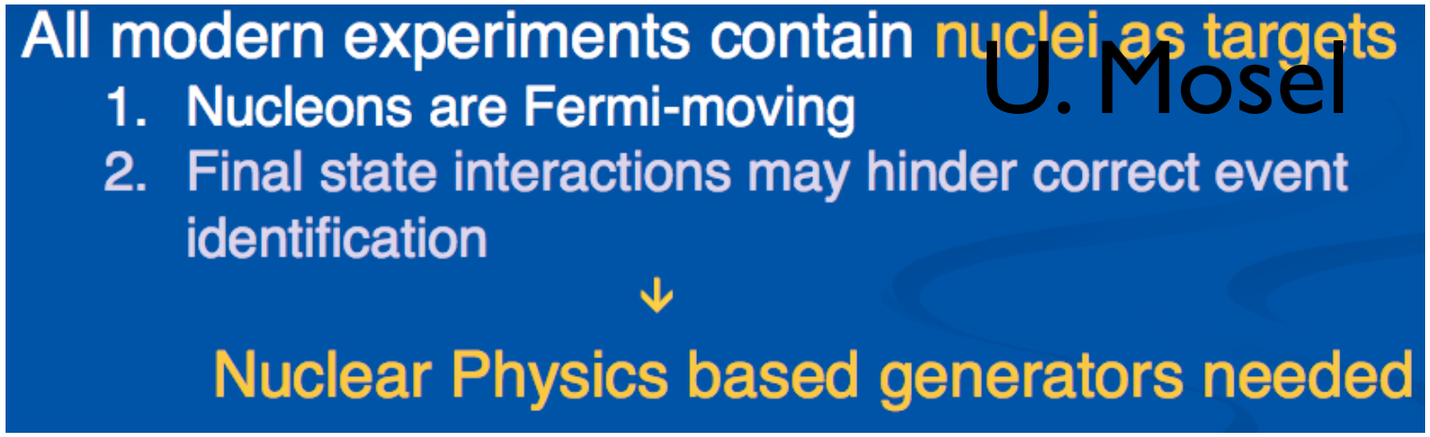
GENIE

μ^+Np
final state events
anti-nu mode

Important to reconstruct also neutrons, in particular at low energy (MicroBooNE)!

Data from LAr extremely helpful and can provide important hints to tune MC generators and discriminate among models.

- **Accurate and extremely detailed MonteCarlo generators are needed for comparison with LAr data, in particular** for nuclear effects understanding

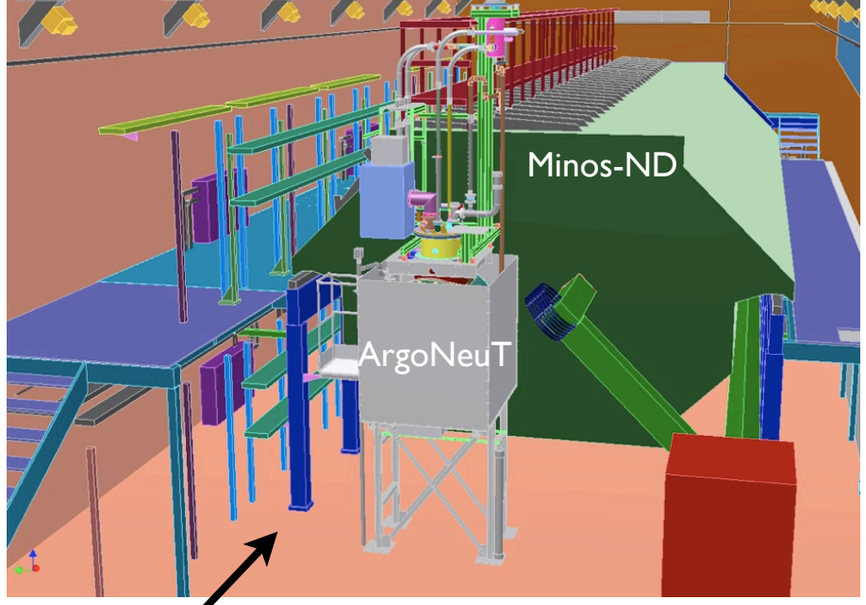


SUMMARY

Progressing with the *development* of more and more accurate *reconstruction tools* for data analysis, in combination with *larger mass LAr-TPC detectors* (MicroBooNE) is an important step for accurate topological analysis of neutrino events, *on the line pioneered by ArgoNeuT*.

Backup

ArgoNeuT

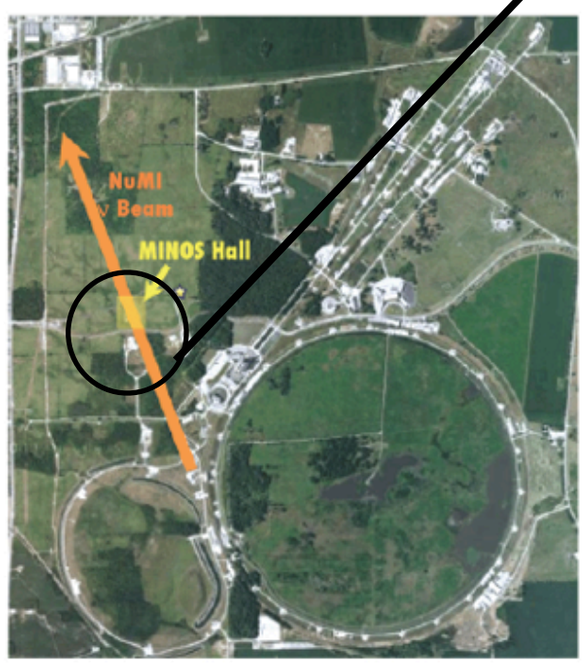


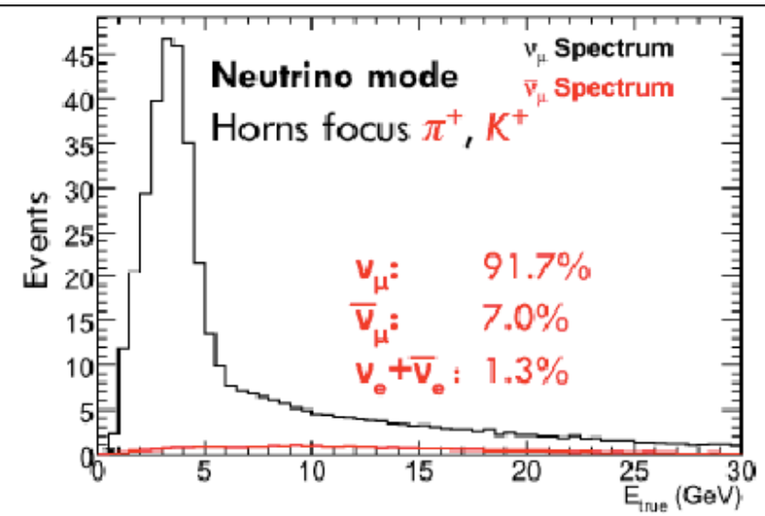
"The ArgoNeuT detector in the NuMI low- energy beamline at Fermilab" JINST 7 P10019 (2012)

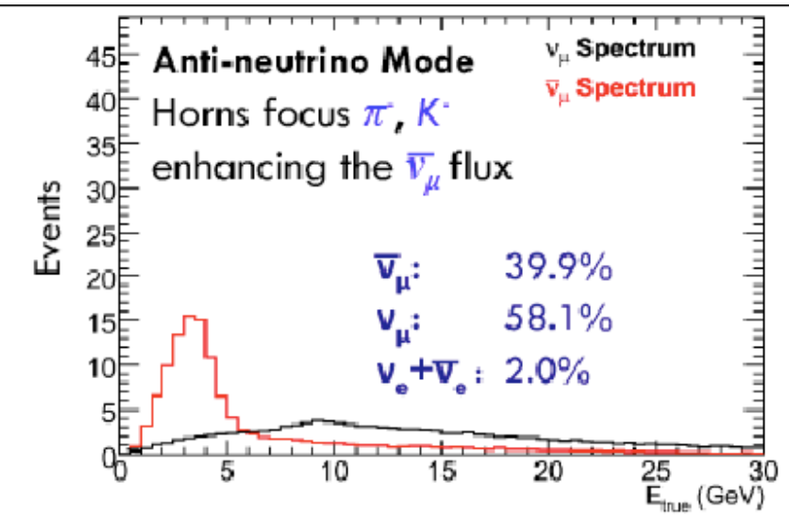
NuMI LE beam
ν–mode (2 weeks): 8.5×10^{18} POT
$\bar{\nu}$–mode (6 months): 1.20×10^{20} POT

175 l active volume

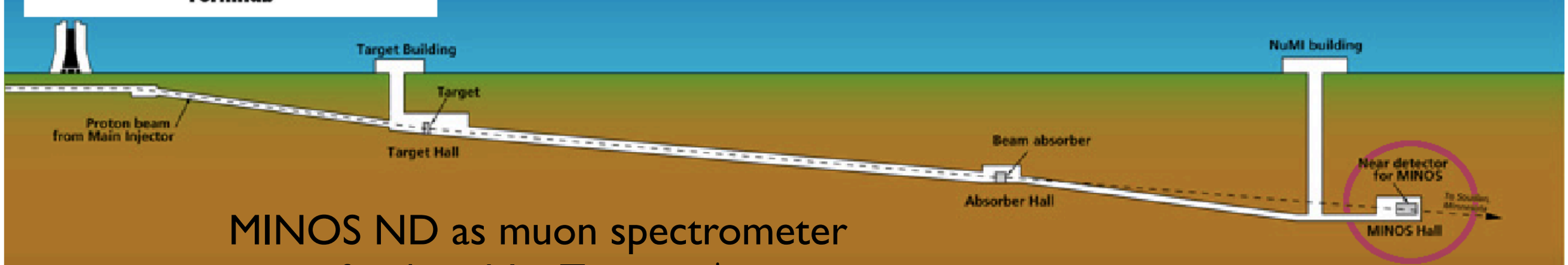
~7000 CC events collected







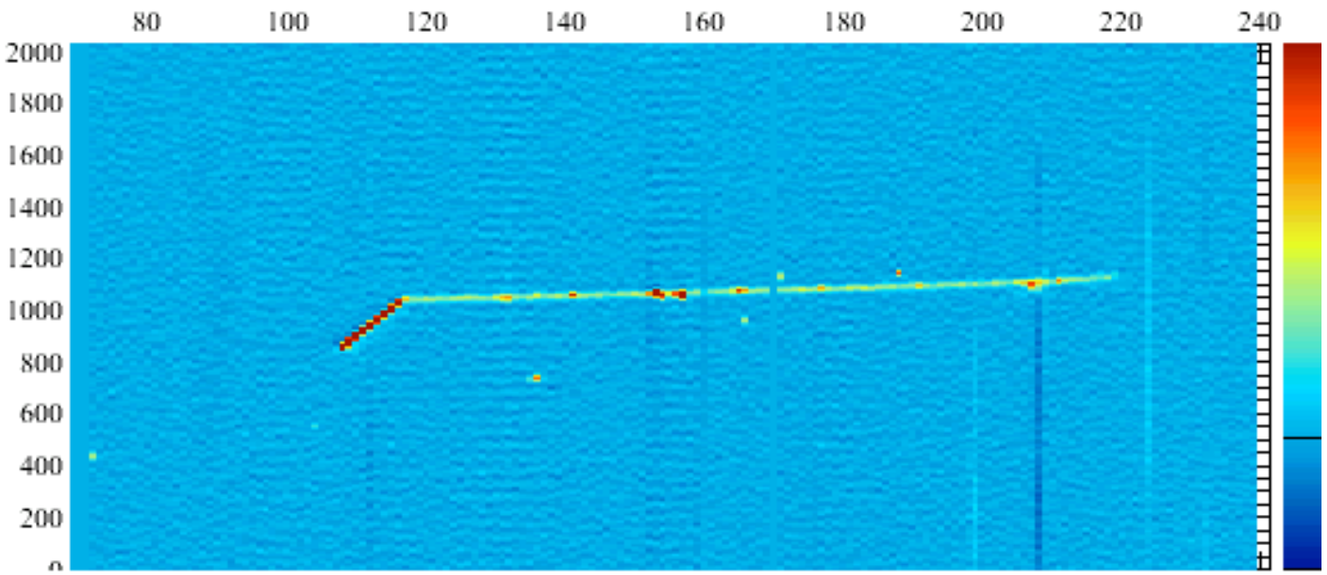
NuMI LE beam

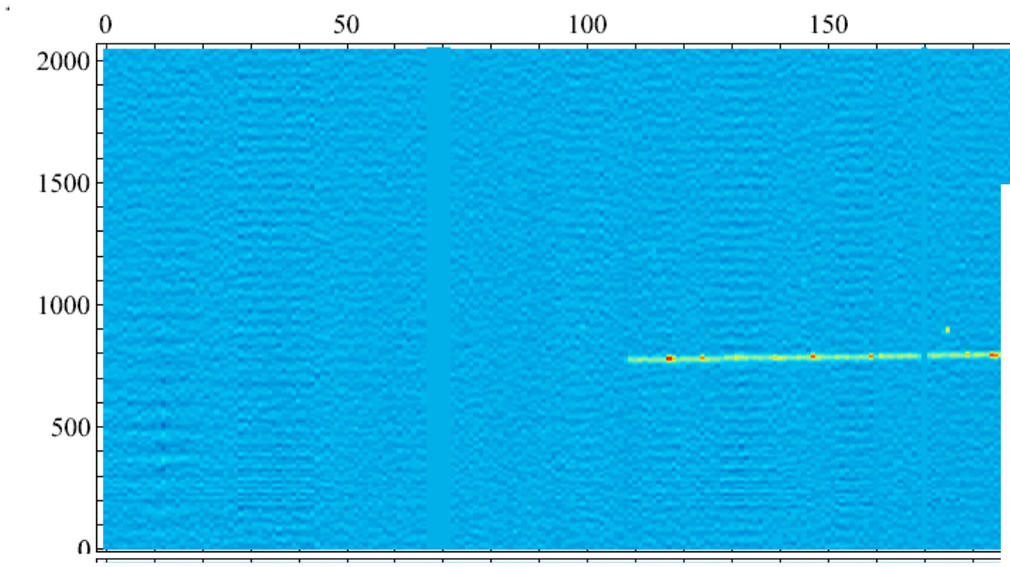


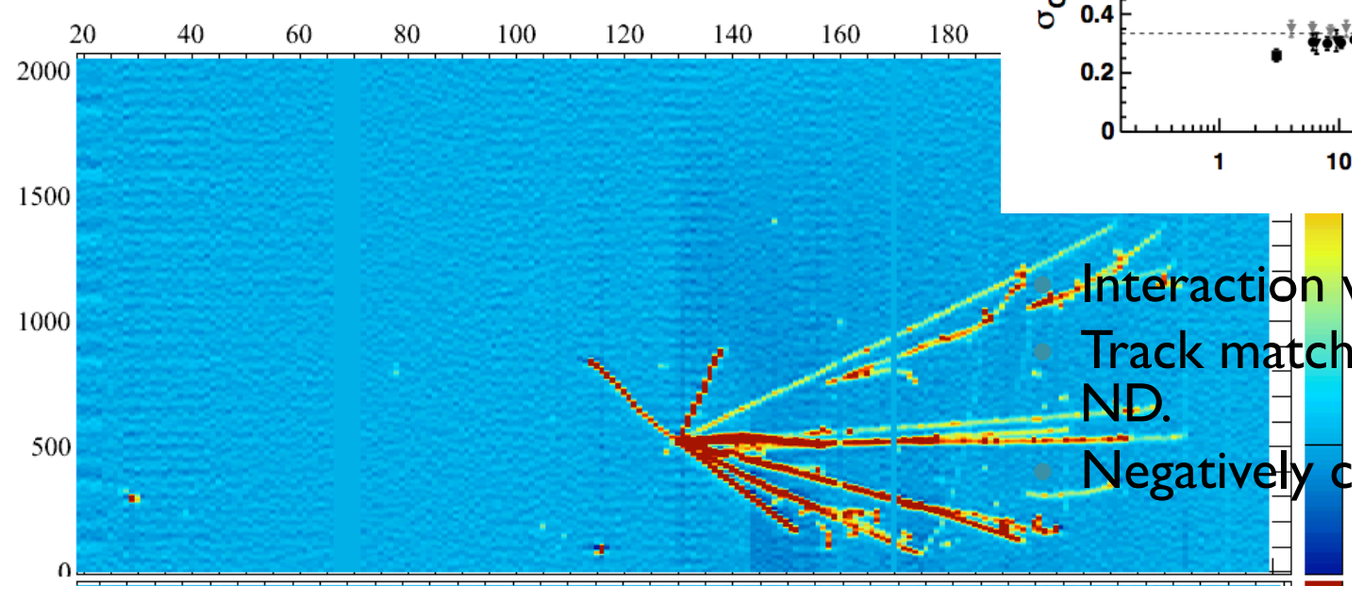
MINOS ND as muon spectrometer for ArgoNeuT events*
(energy reconstruction and charge identification (q) of exiting muons)

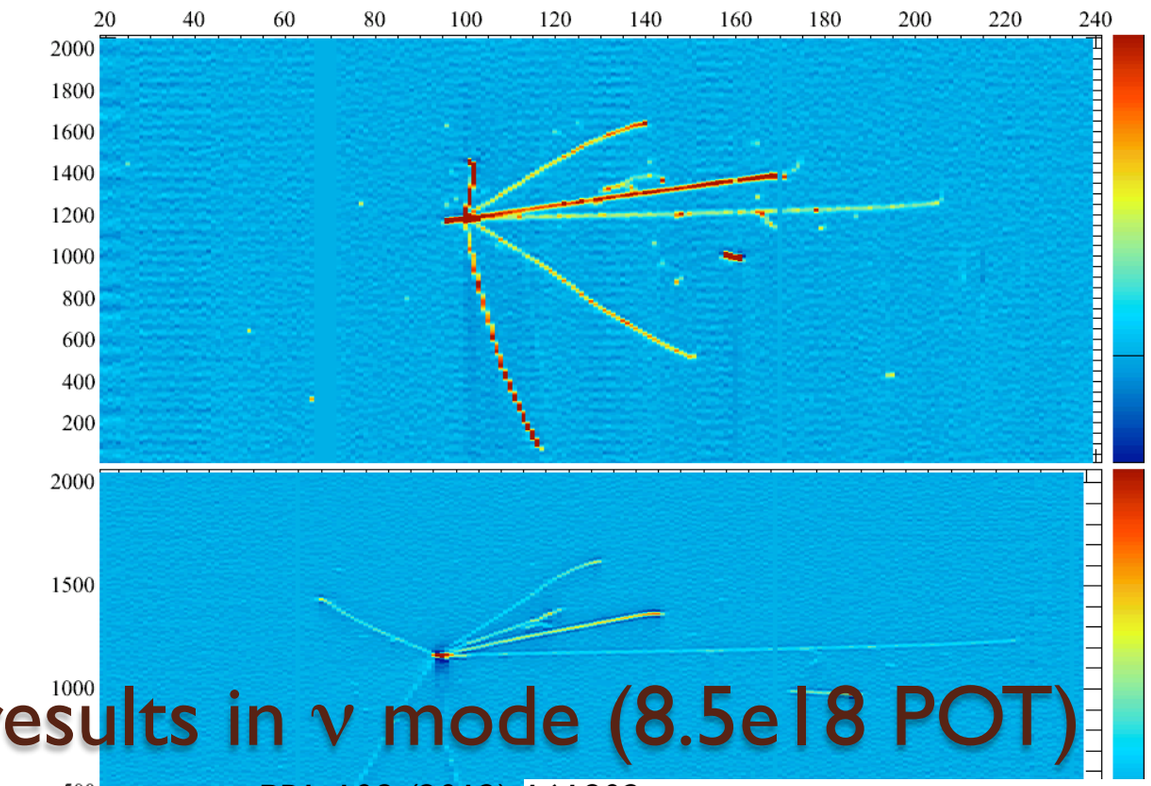
**ArgoNeuT Coll. is grateful to MINOS Coll. for providind the muon reconstruction*

ArgoNeuT ν_μ CC inclusive



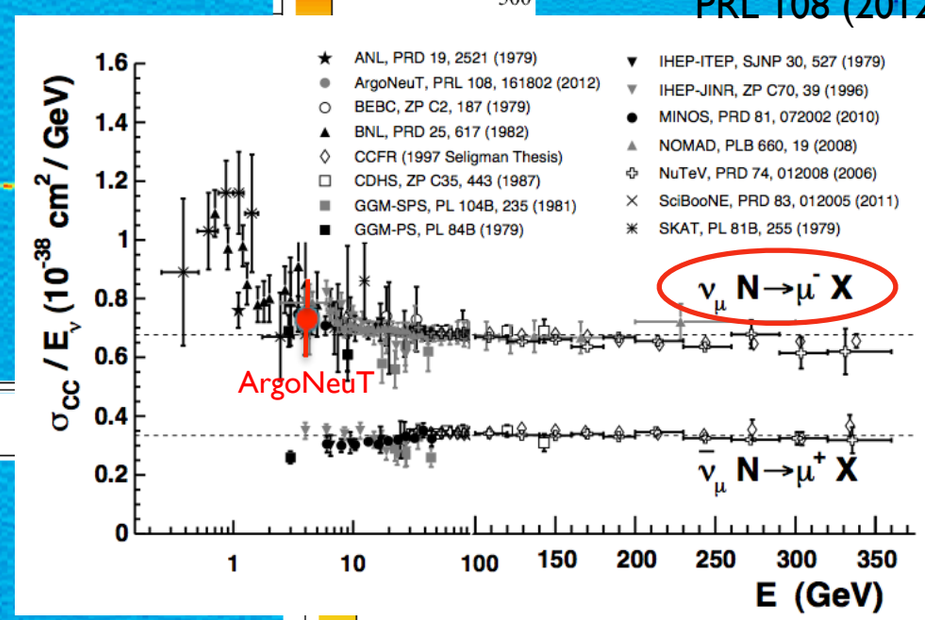


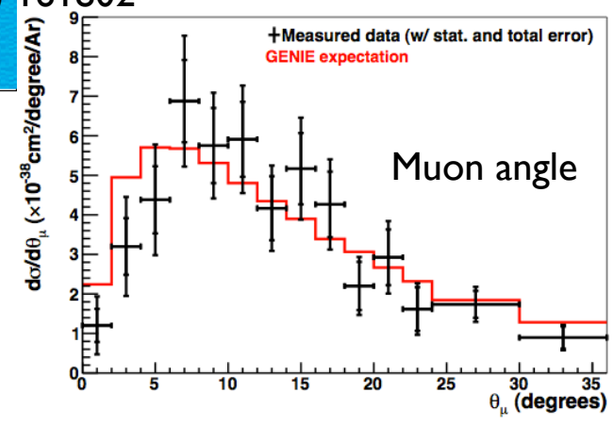


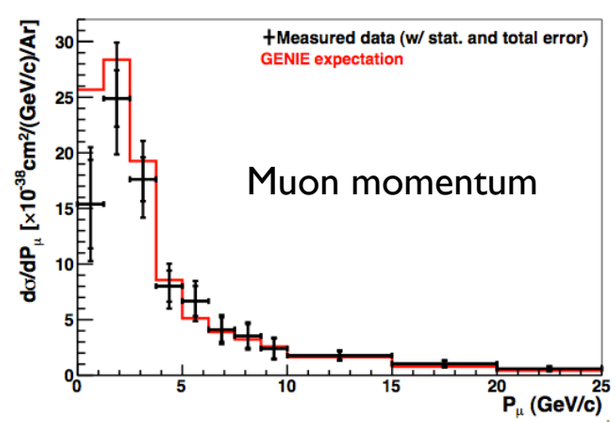


Previous results in ν mode (8.5e18 POT)

PRL 108 (2012) 161802

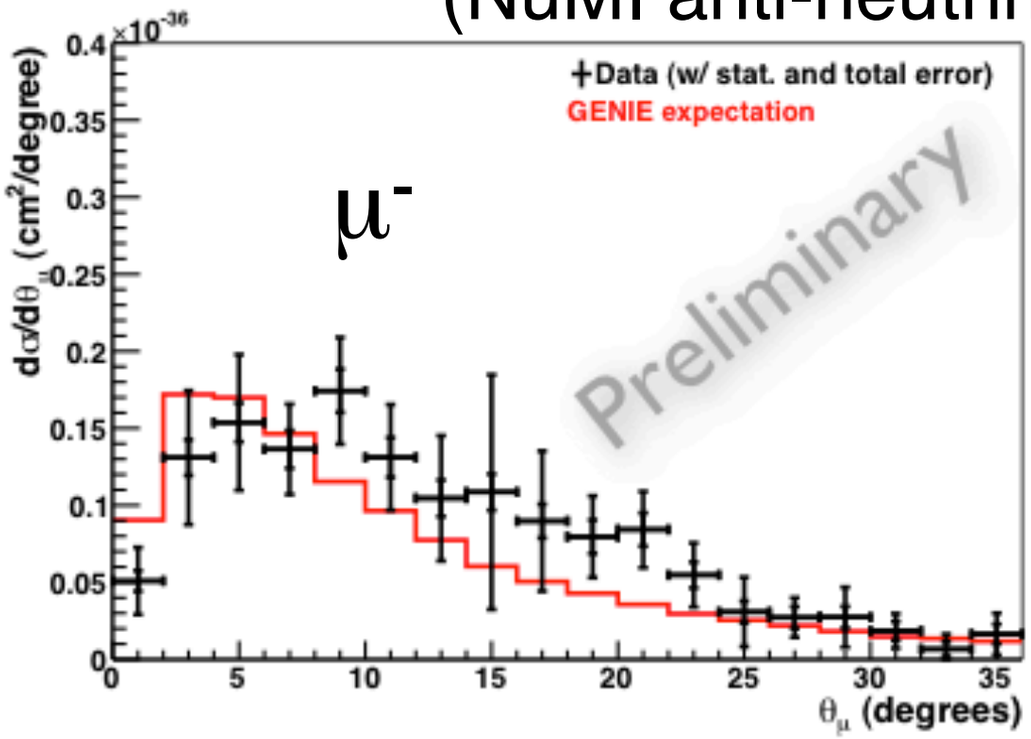


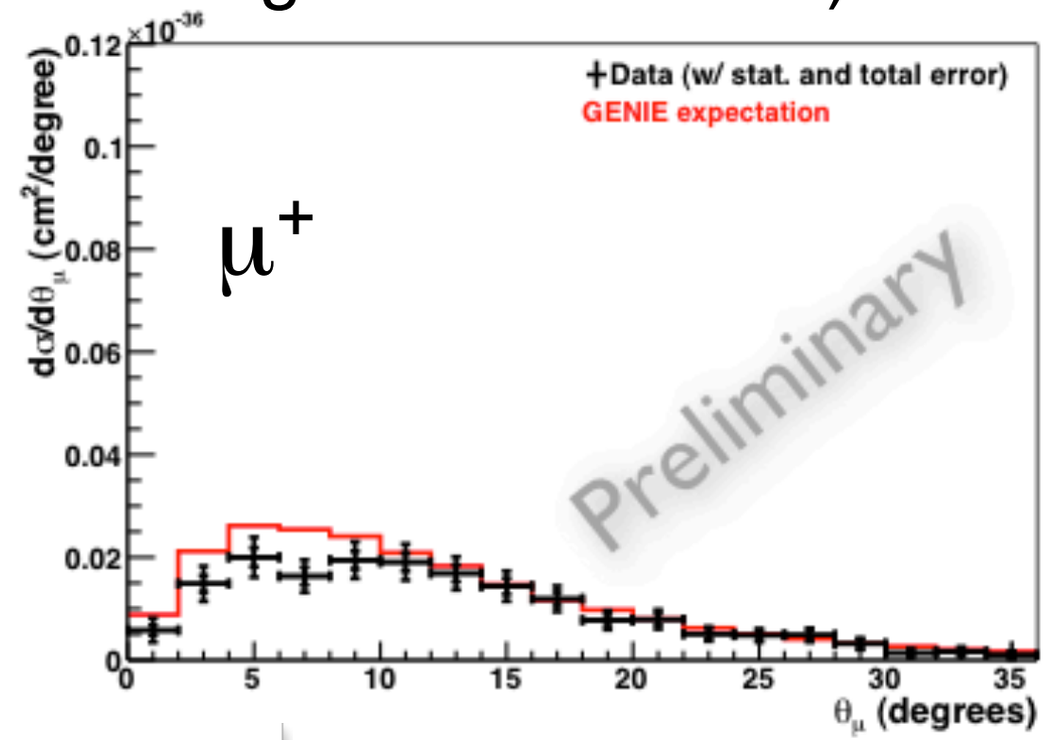




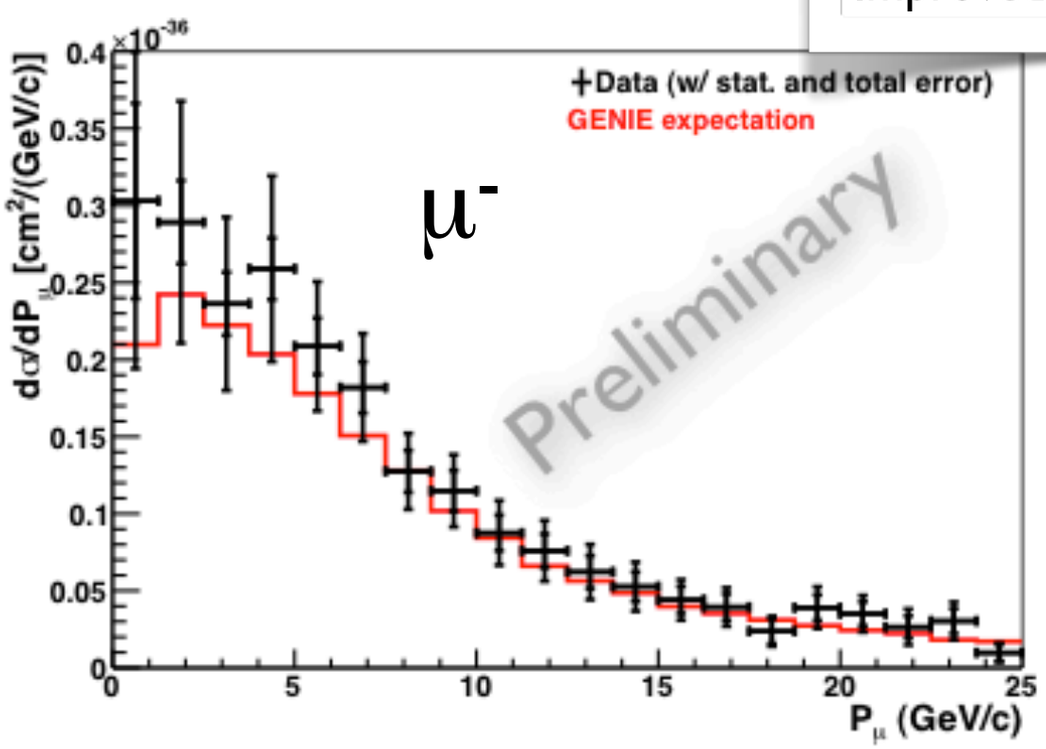
- Interaction vertex in fiducial volume.
- Track matched to muon in MINOS ND.
- Negatively charged muon in MINOS.

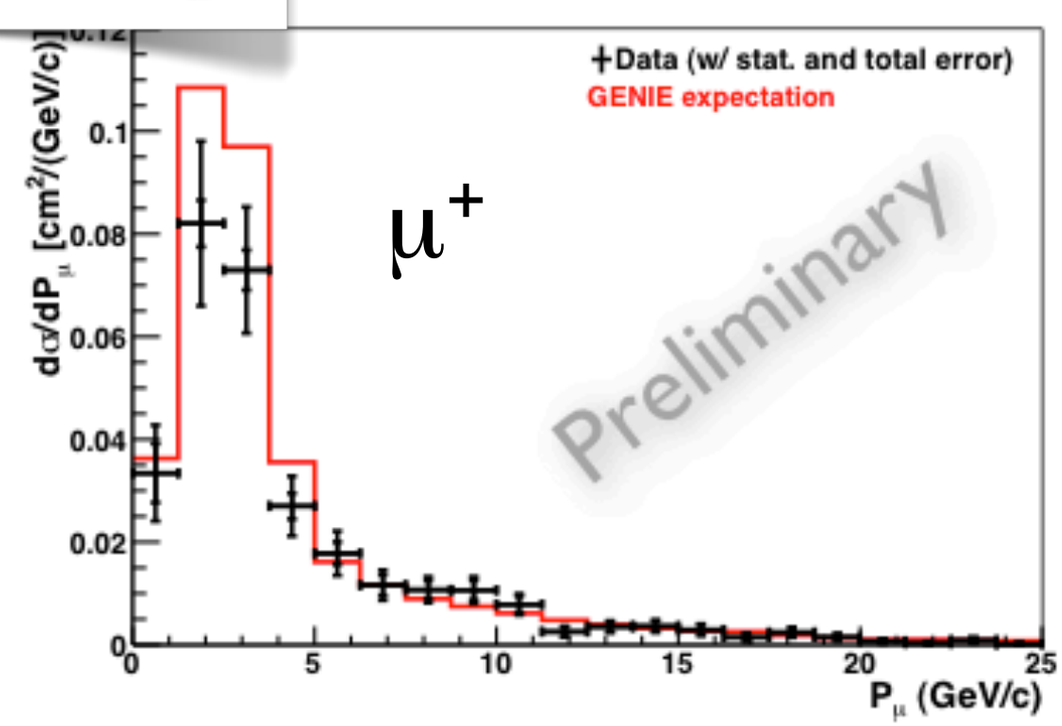
ν_μ and $\overline{\nu}_\mu$ differential cross-sections
(NuMI anti-neutrino mode running - 1.25E20 POT)



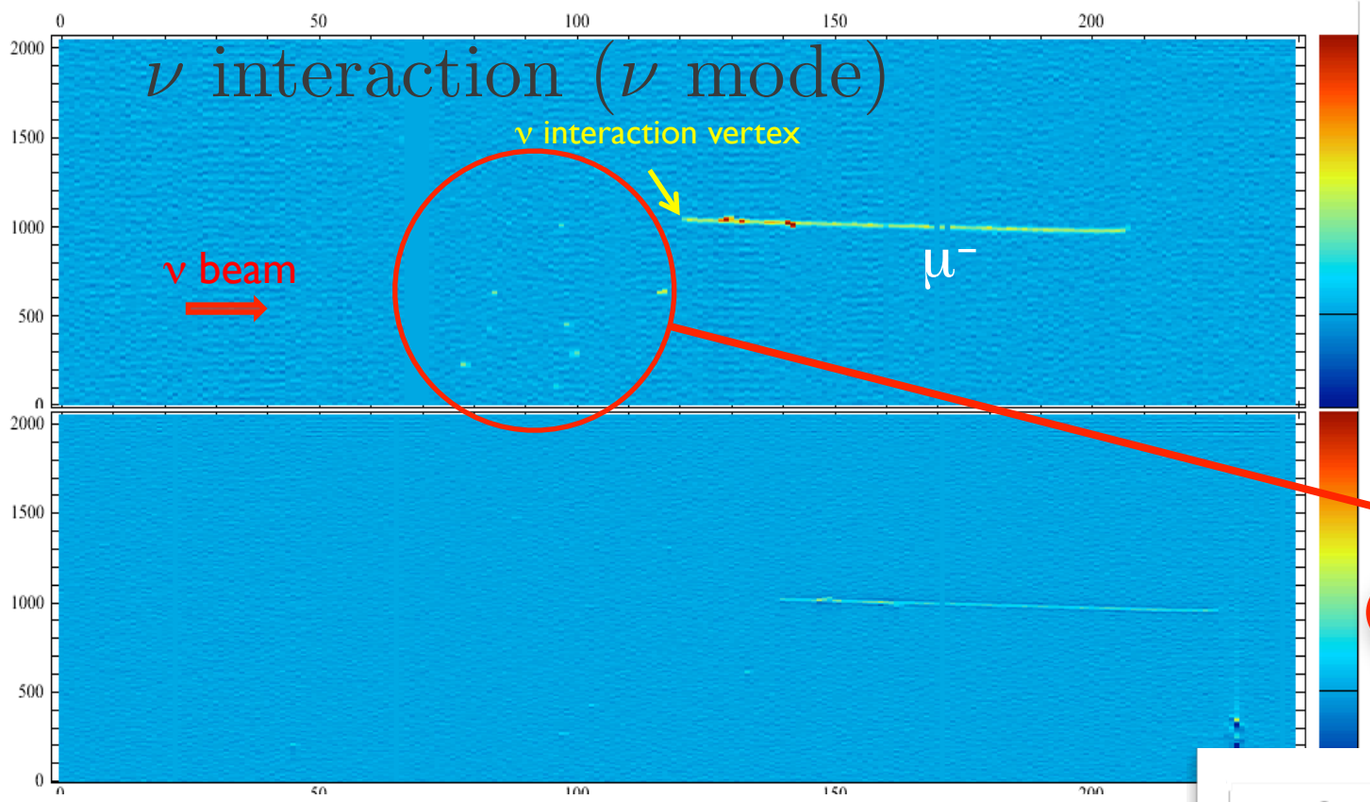


Default FLUKA flux.
Improved flux tuning to be used



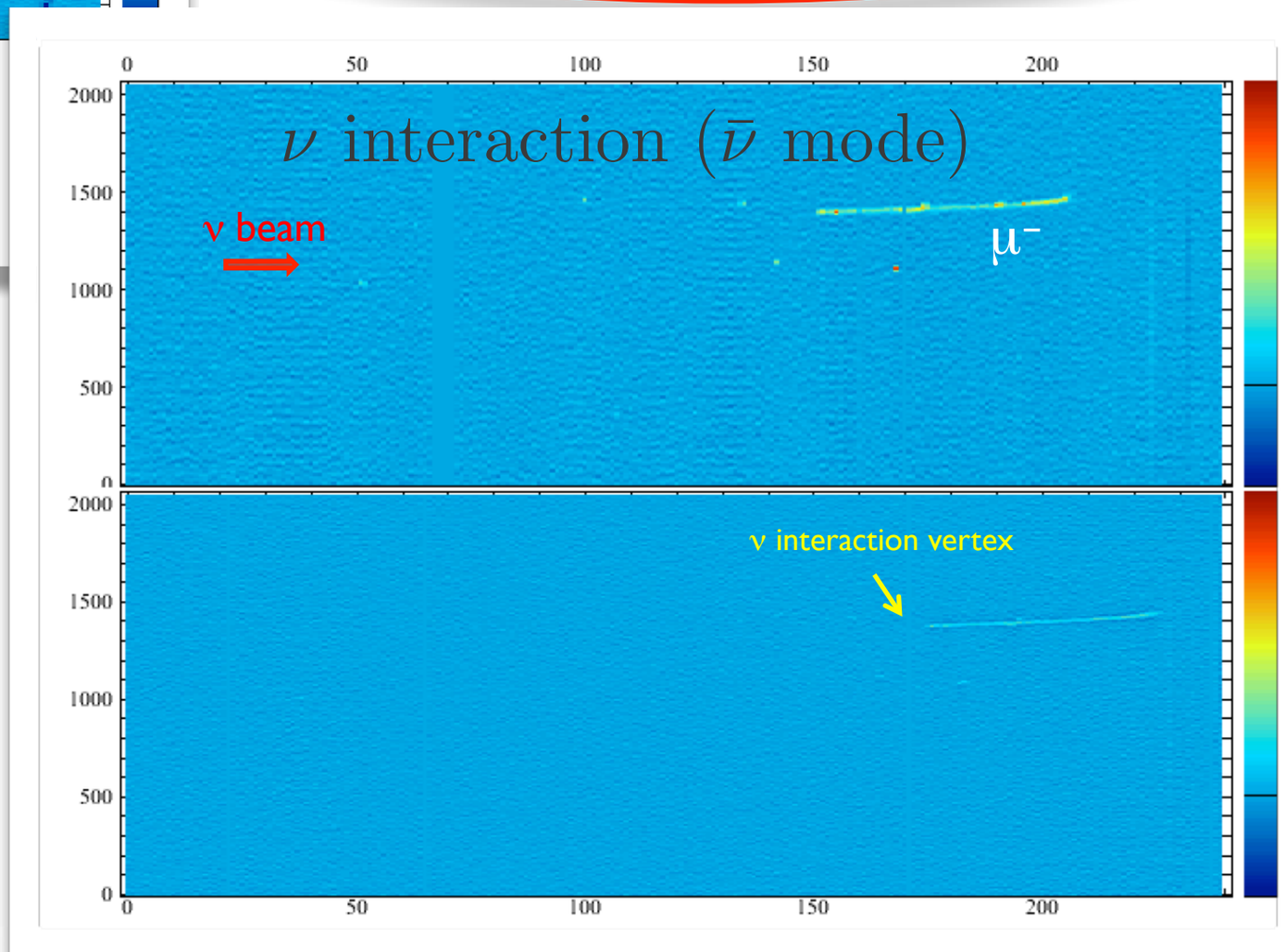


DATA: EXCLUSIVE TOPOLOGIES



Activity around the vertex

e's from nuclear de-excitation **γ** conversion



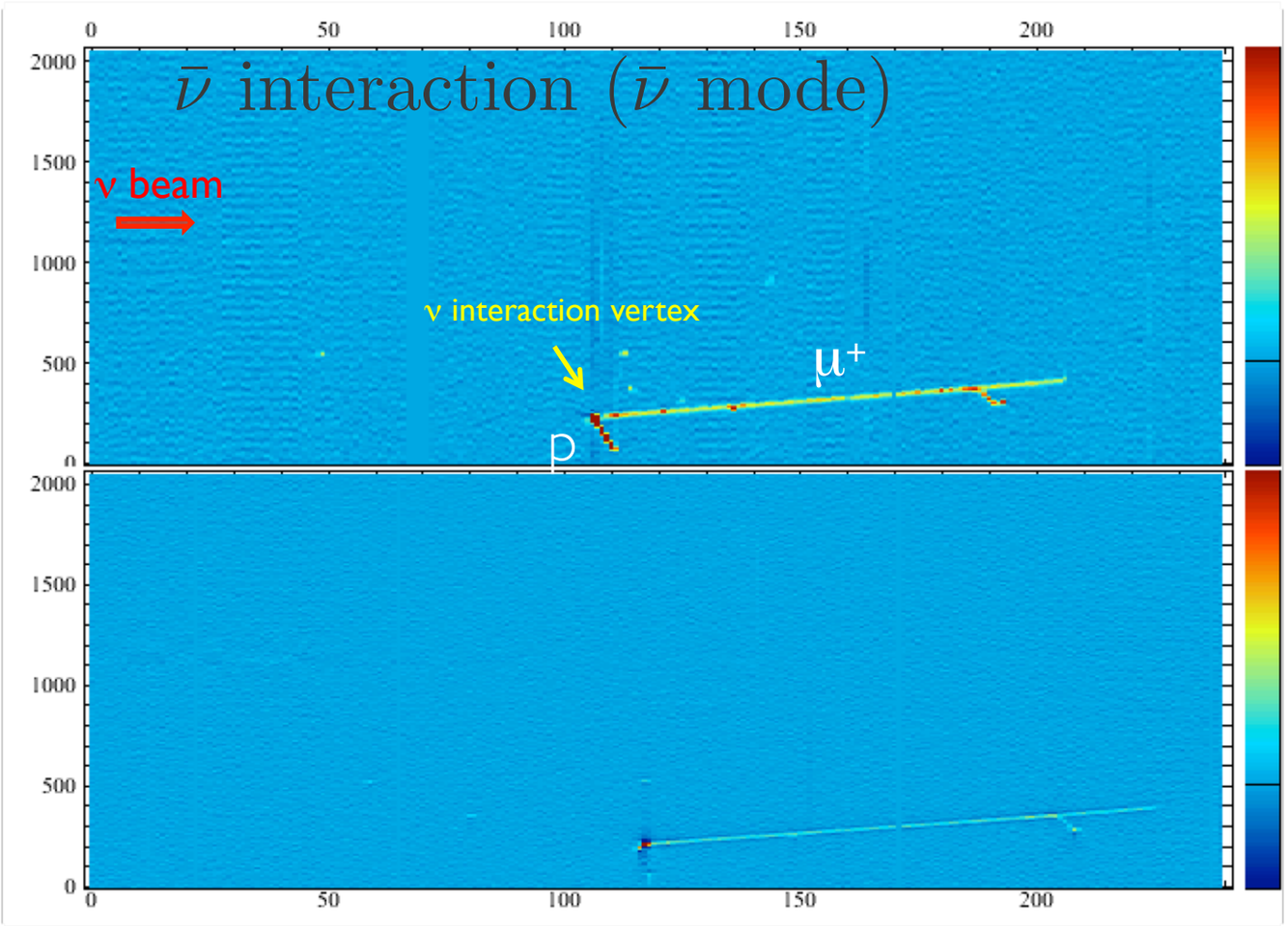
1 track: μ^-

μ^- track only, no p at the vertex

Evidence of FSI!

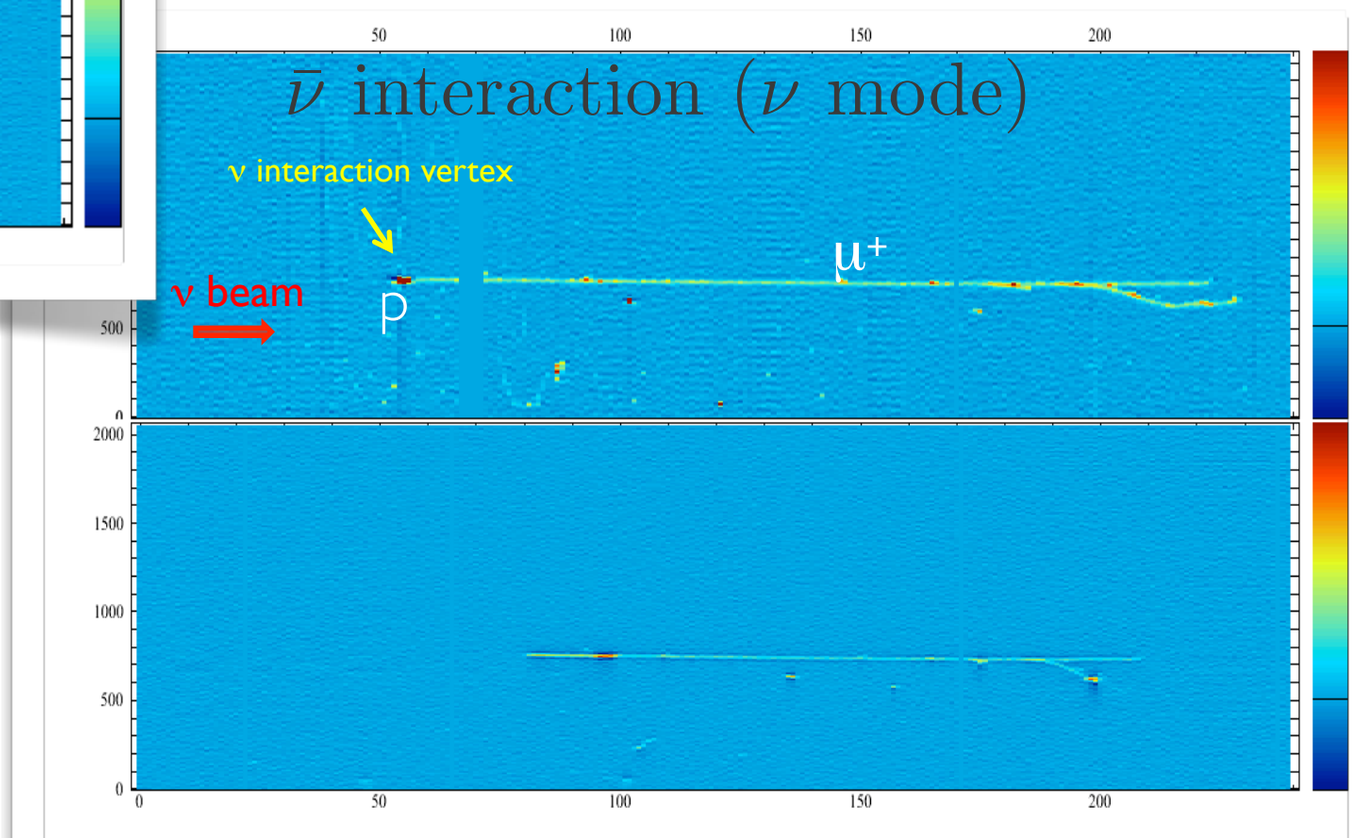
ν_μ CC events: $\mu^- 0\mathrm{p}$

DATA: EXCLUSIVE TOPOLOGIES



Activity around the vertex

e's from nuclear de-excitation **γ** conversion



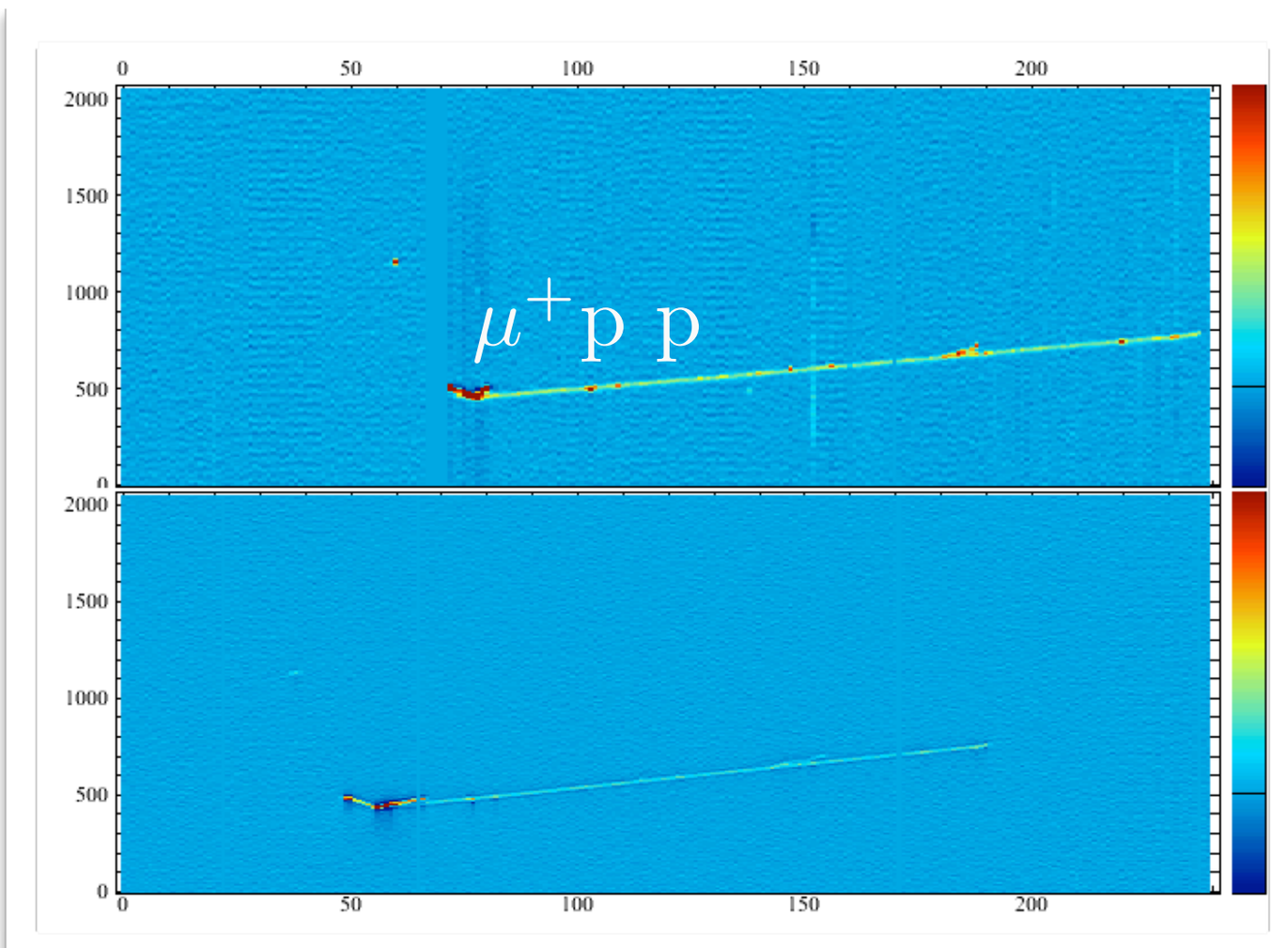
2 tracks: 1 μ^+ 1 p

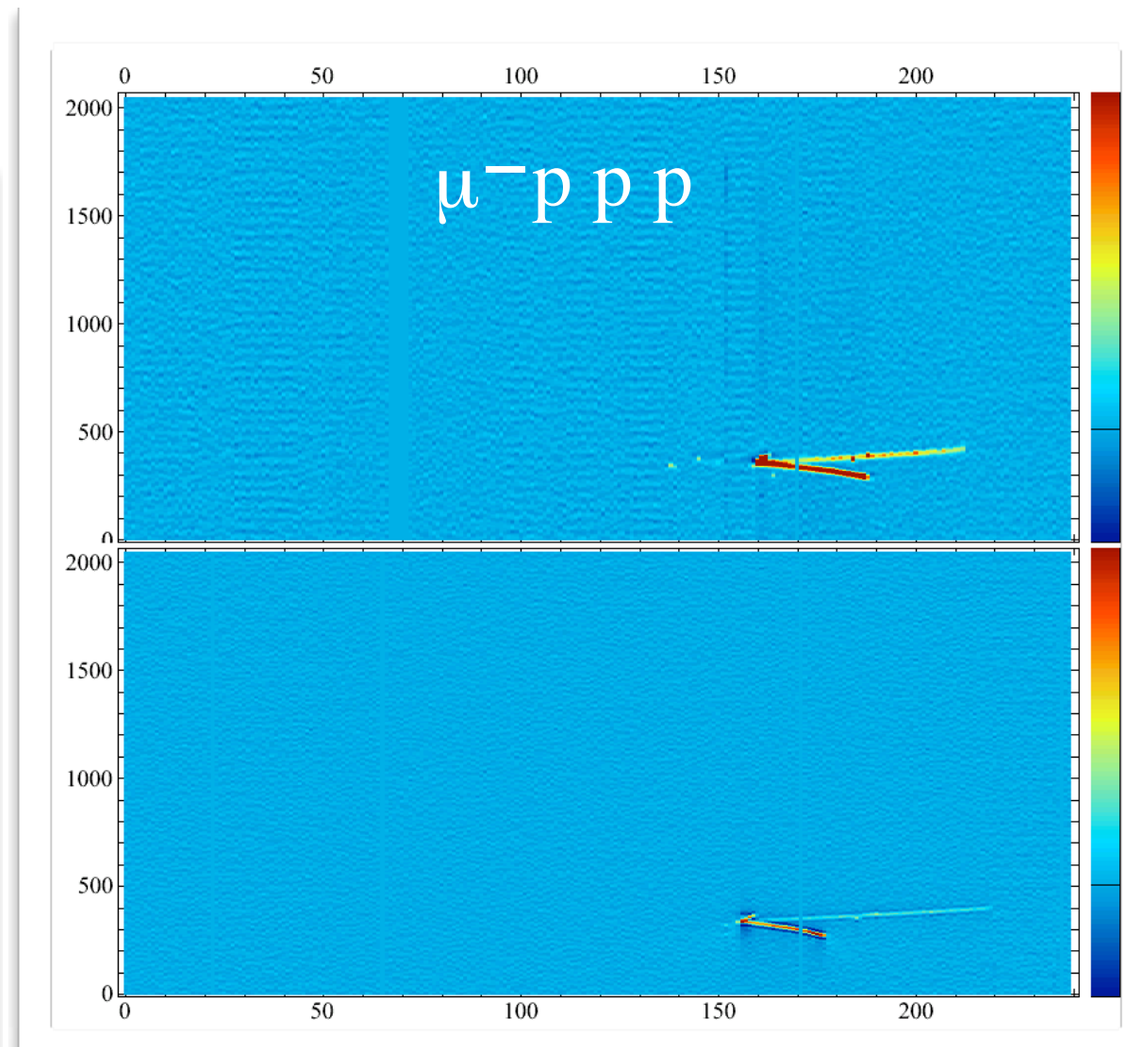
Evidence of FSI!

$\bar{\nu}_\mu$ CC events: μ^+p

DATA: EXCLUSIVE TOPOLOGIES

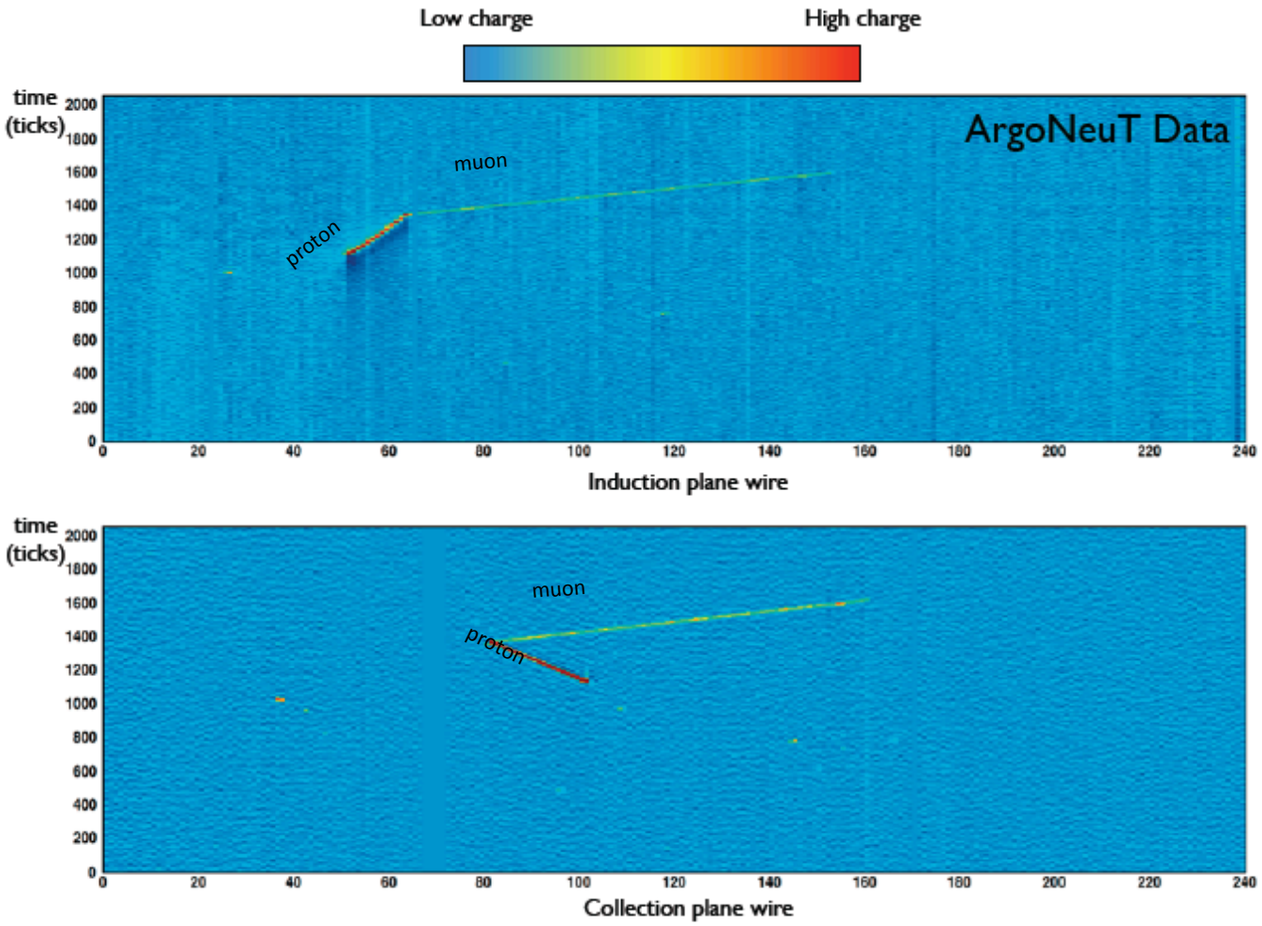
Multi-p accompanying
the leading muon
+ γ activity in the volume
around the vertex



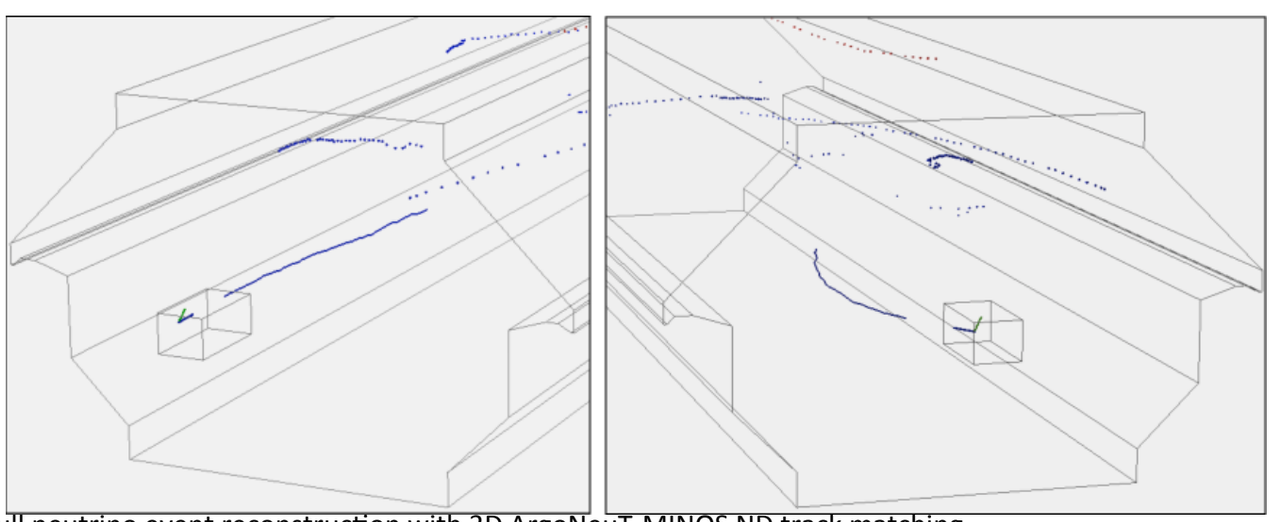


$\nu_\mu/\bar{\nu}_\mu$ CC events: $\mu^{-/+}$multi-proton

Reconstruction of $1\mu 1p$ events



μ- escaping ArgoNeuT (and reaching MINOS-ND downstream)

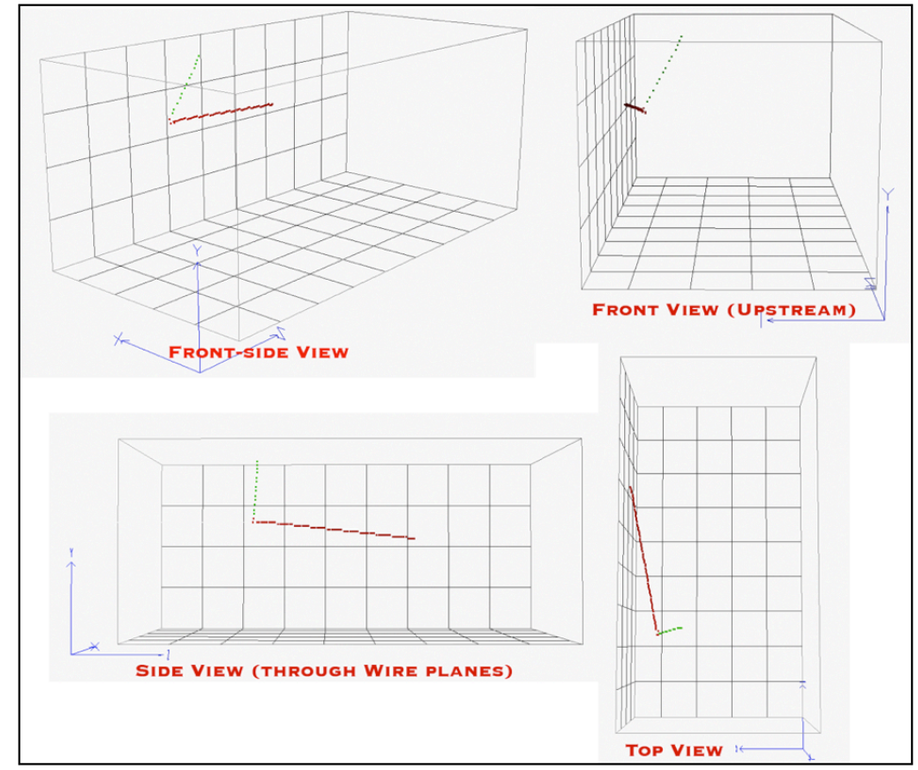


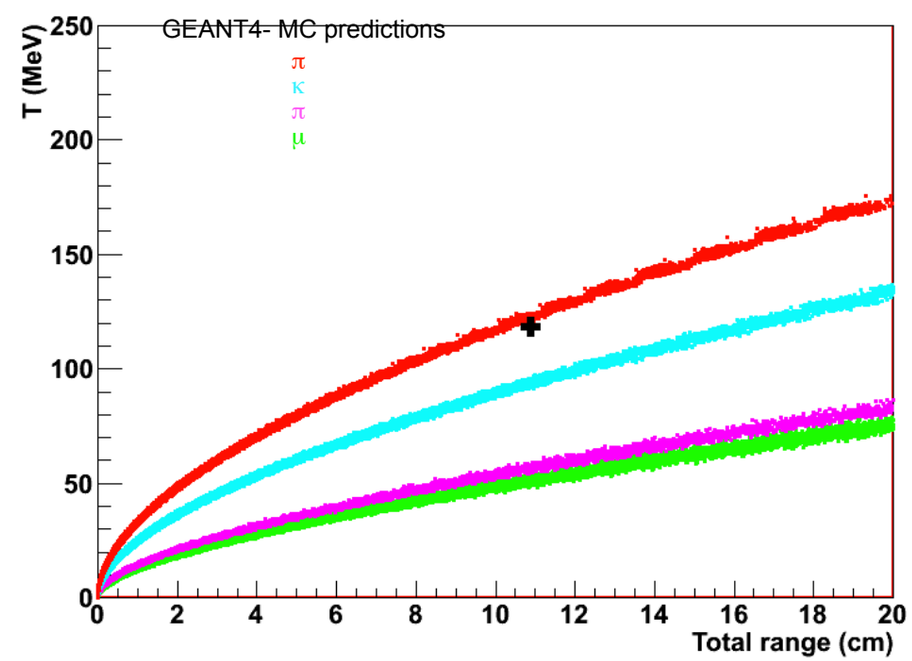
Full neutrino event reconstruction with 3D ArgoNeuT-MINOS ND track matching

$\mu + p$ kinematics — Reconstructed Neutrino Energy= 3.1 GeV

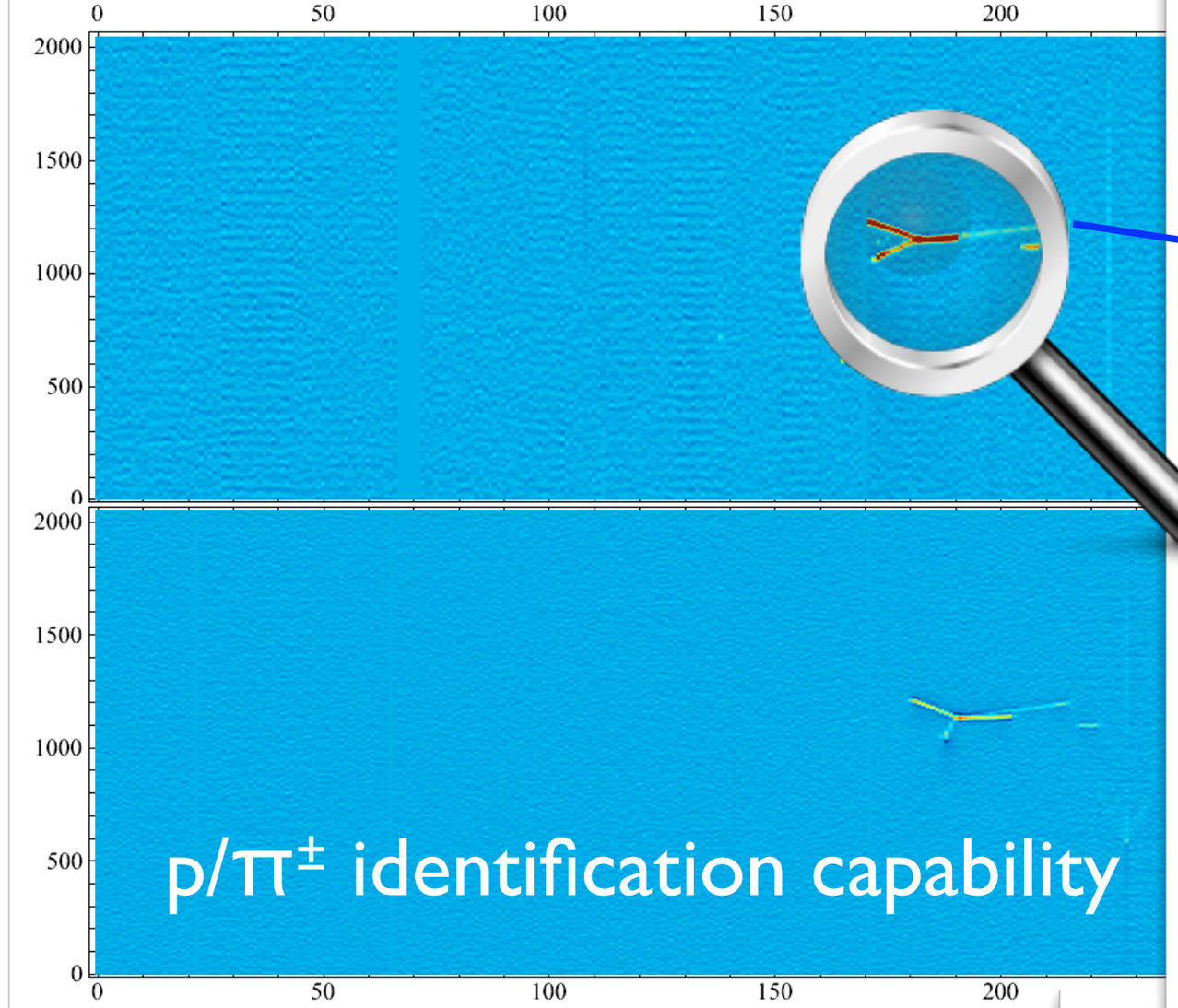
μ kinematics — Reconstructed Neutrino Energy= 3.0 GeV

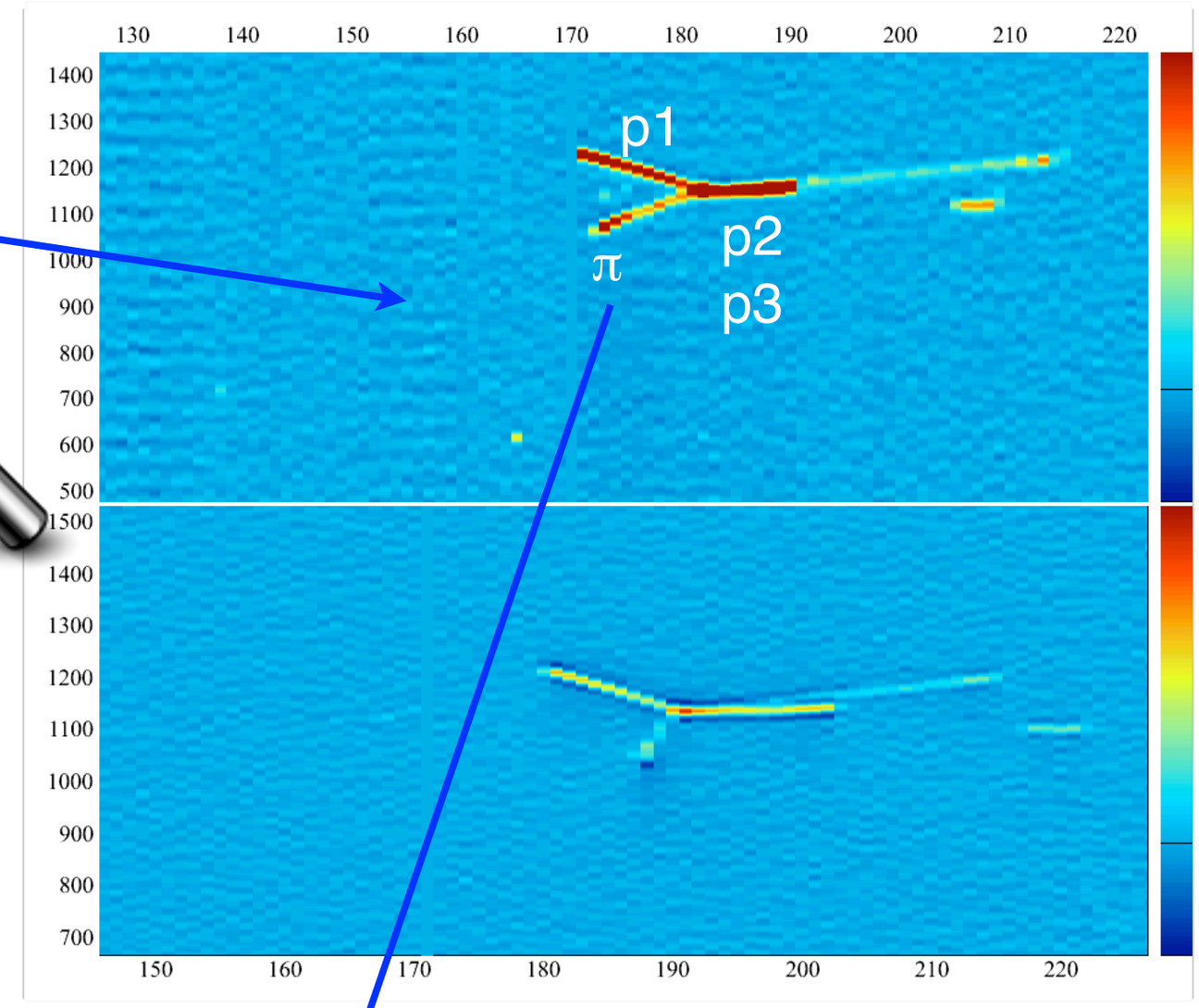
Neutrino event reconstructed in 3D space

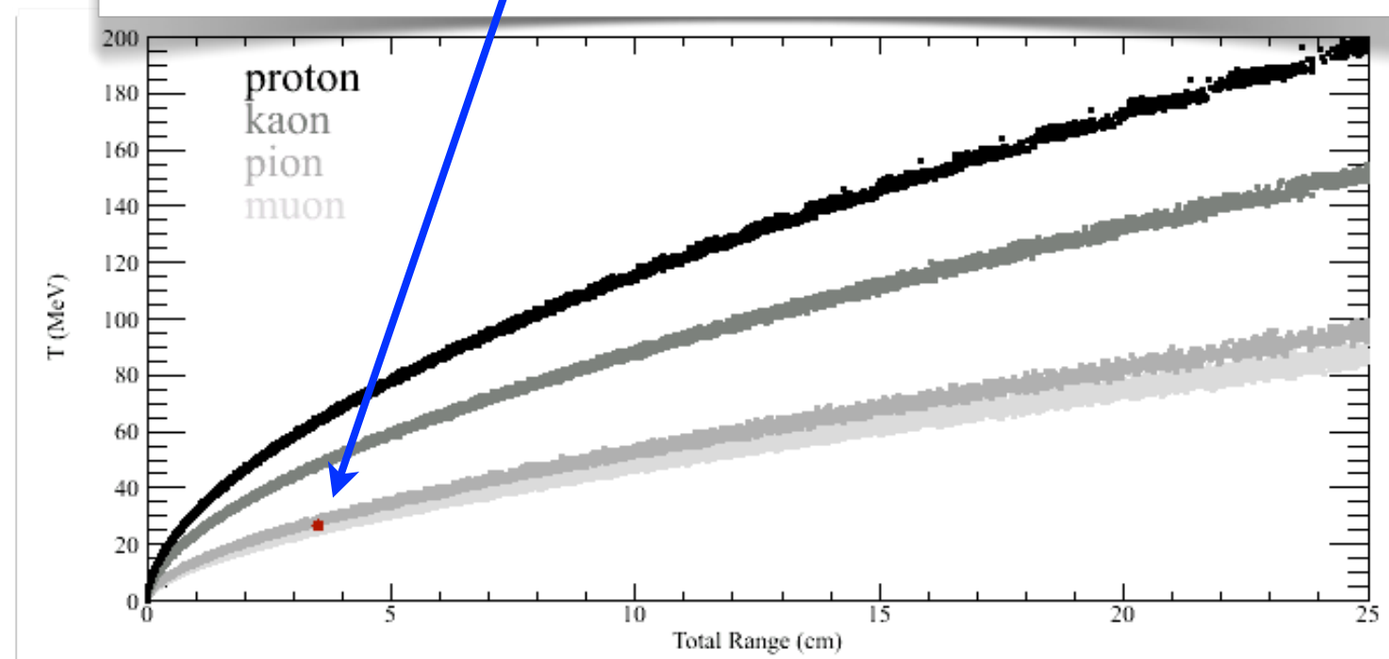




Proton (ArgoNeuT reconstruction): track length= 10.88 cm,
T=118 MeV, p=0.485 GeV/c







- *p1*: 4.9 cm ----> T=83±5 MeV
- *p2*: 5 cm ----> T=134±7 MeV
- *p3*: 5 cm ----> T=134±7 MeV
- π: 3.5 cm ----> T=26±3 MeV

1μ 3p 1π

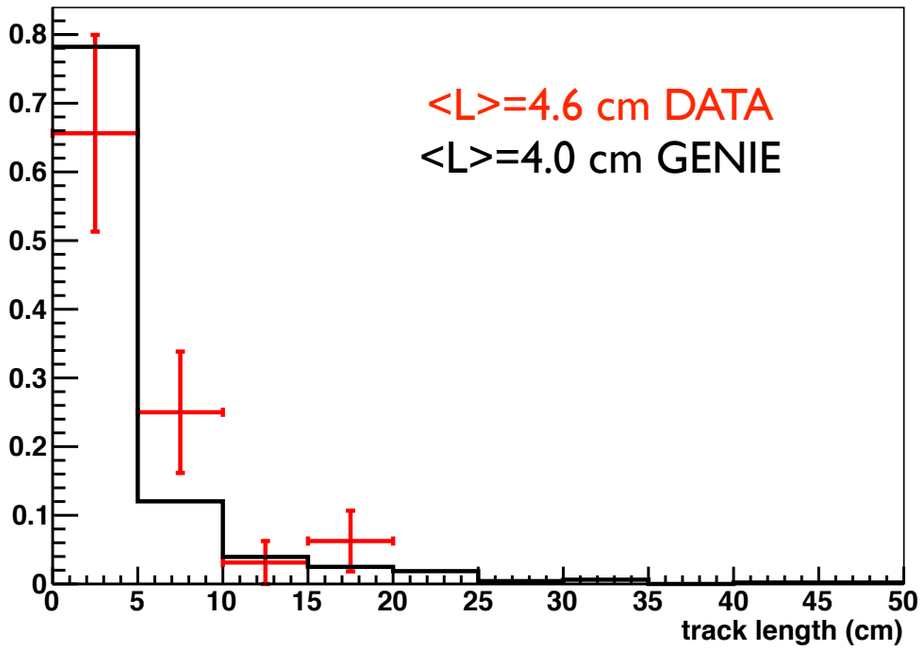
⇒ Event not in the muon+Np sample

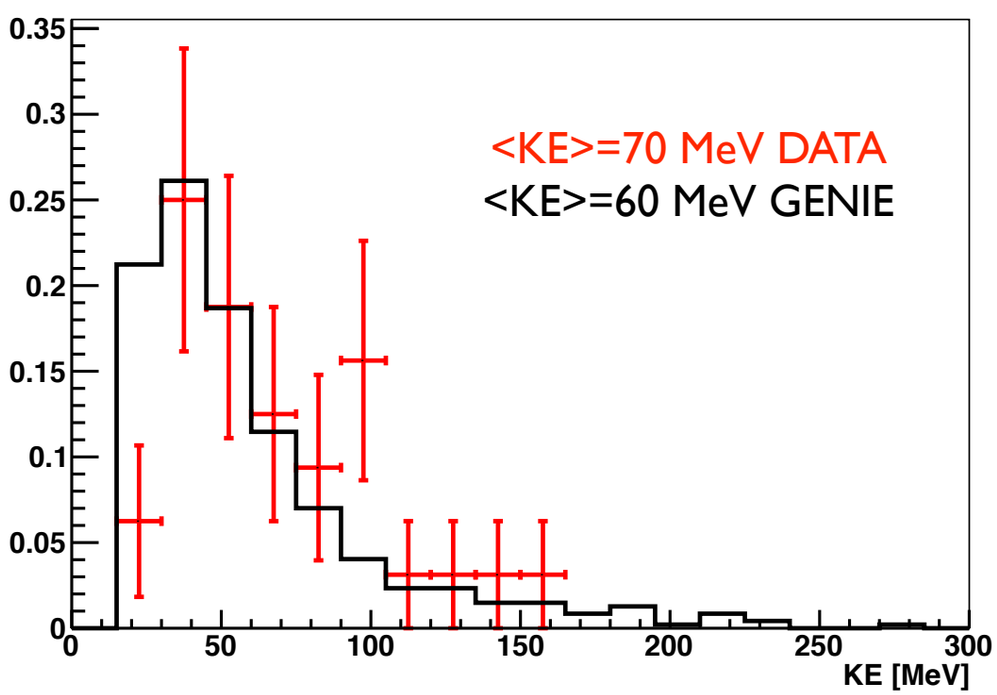
μ^+ / μ^- 2p events

PROTON KINEMATICS
(Event-by event protons reconstruction)

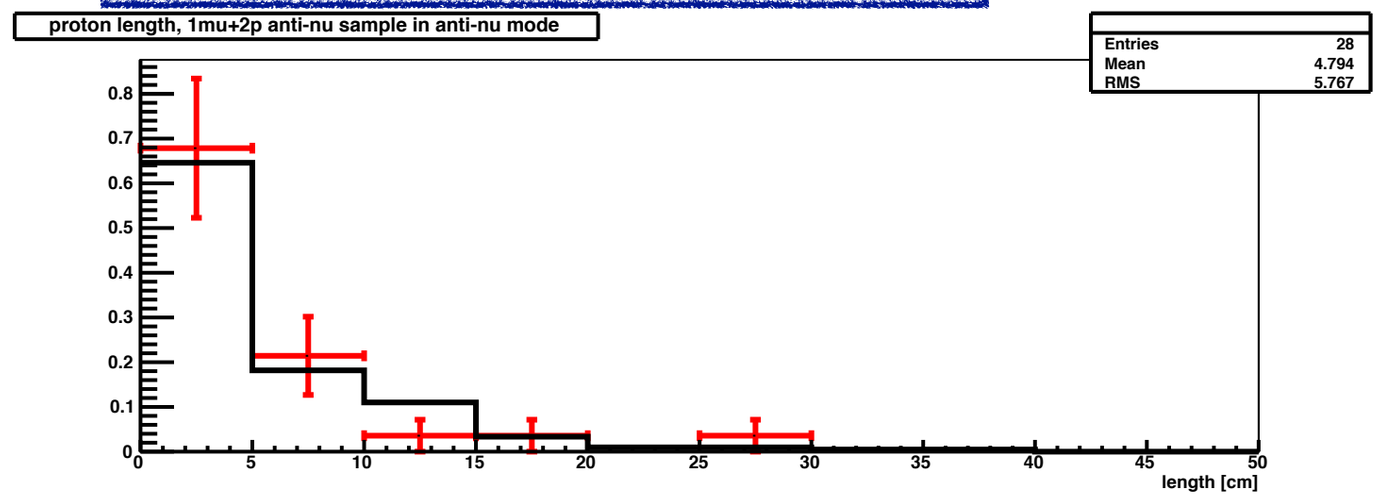
ArgoNeuT

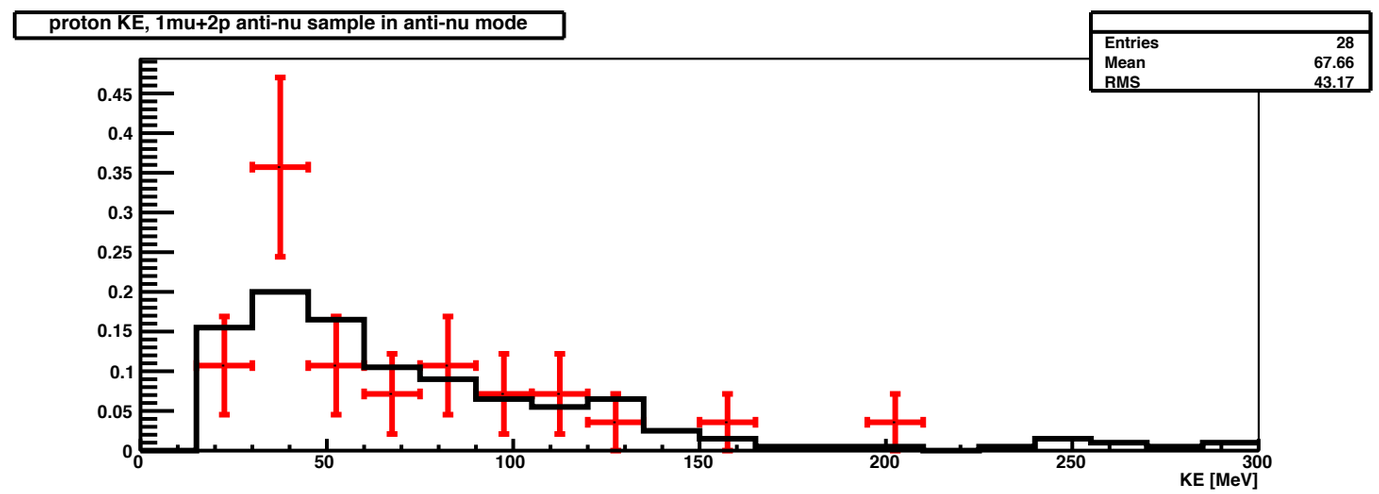
$\bar{\nu}_\mu$ - anti-neutrino mode run



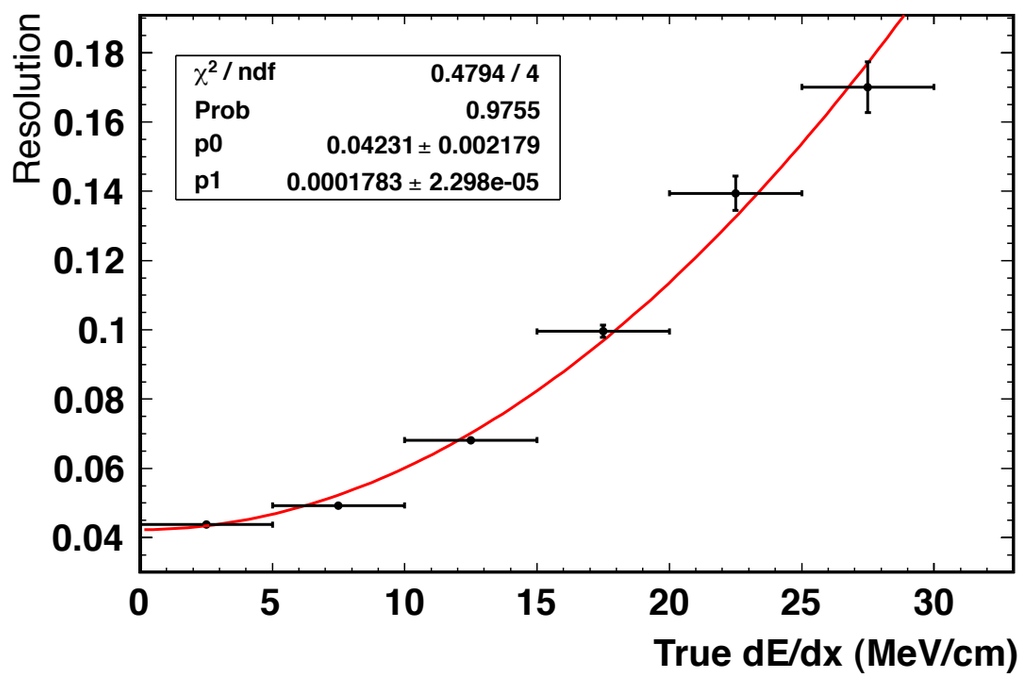


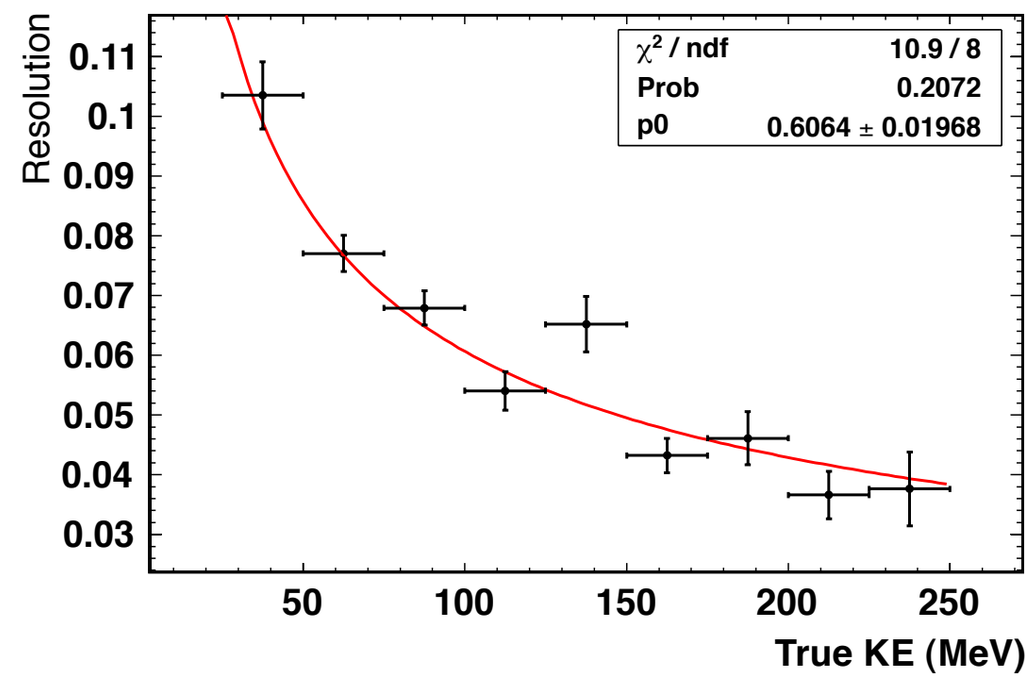
ν_μ - anti-neutrino mode run





area normalized
comparison inside the detector





ArgoNeuT (4 mm wire pitch) Resolution in dE/dx and Kinetic Energy

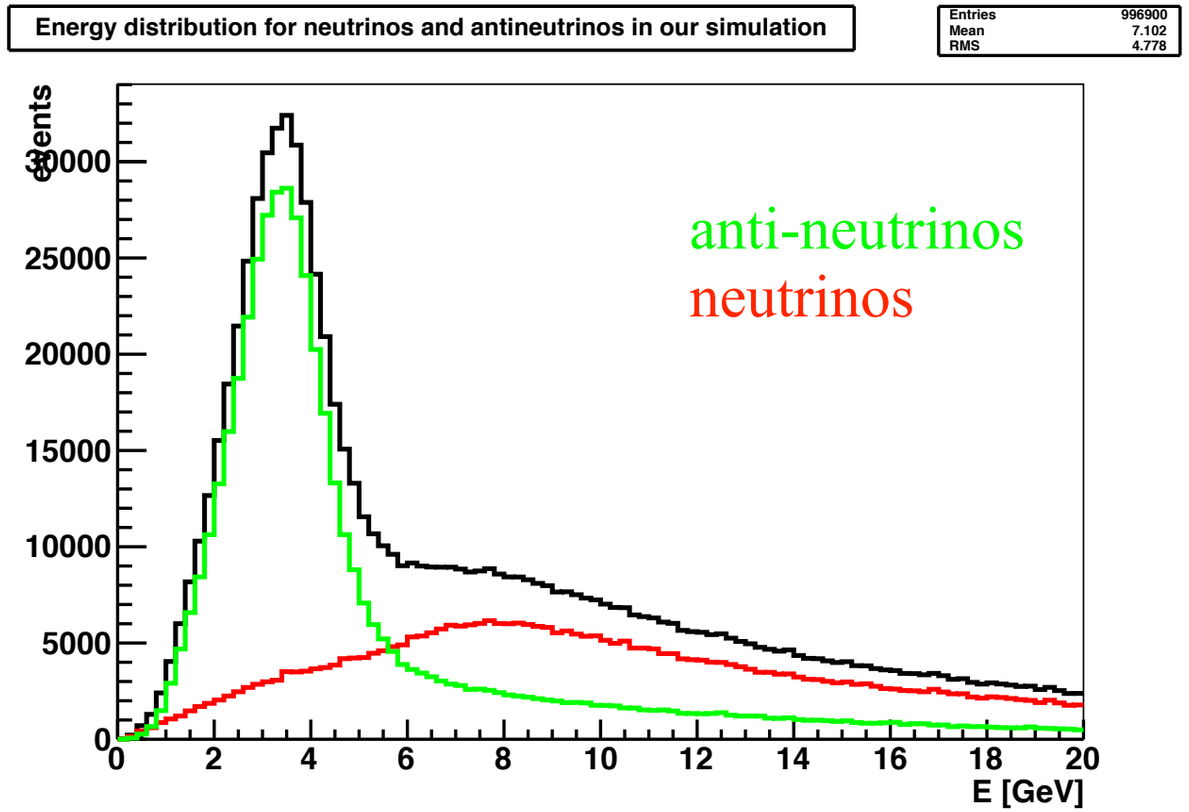
PID Efficiencies

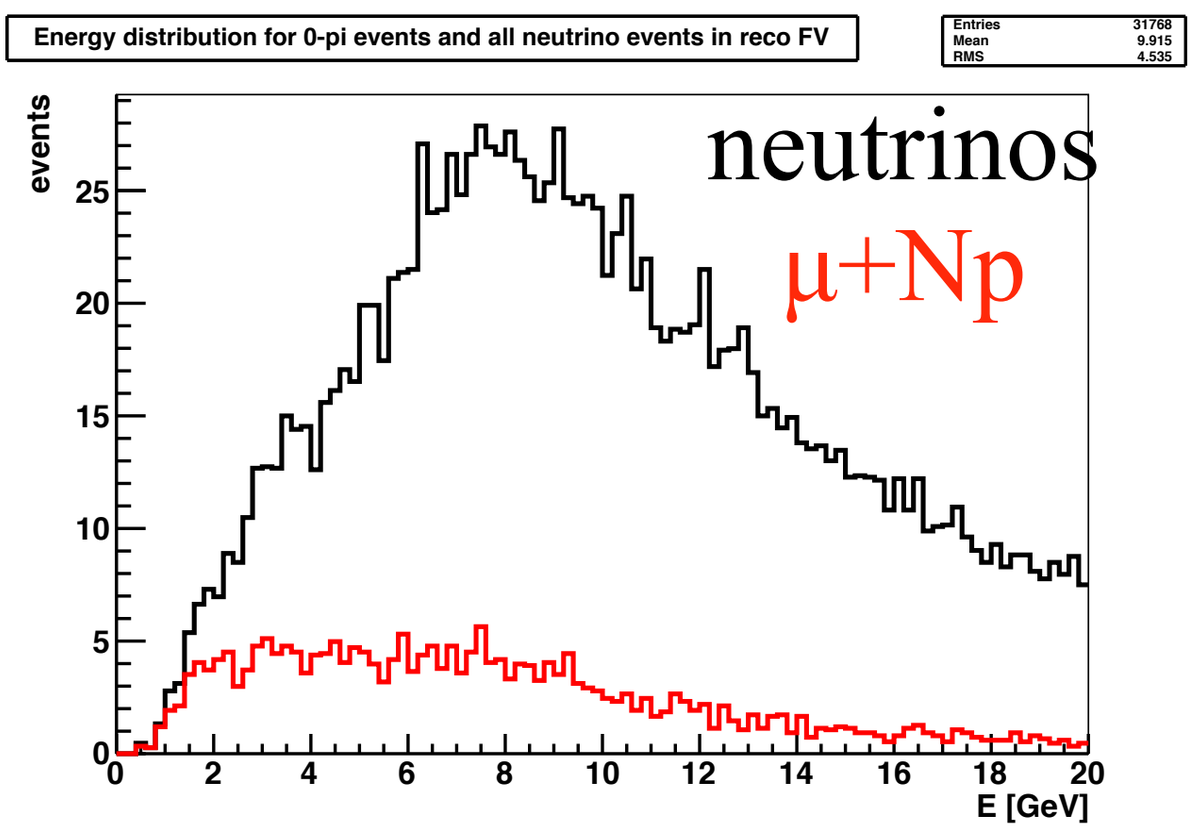
Generated

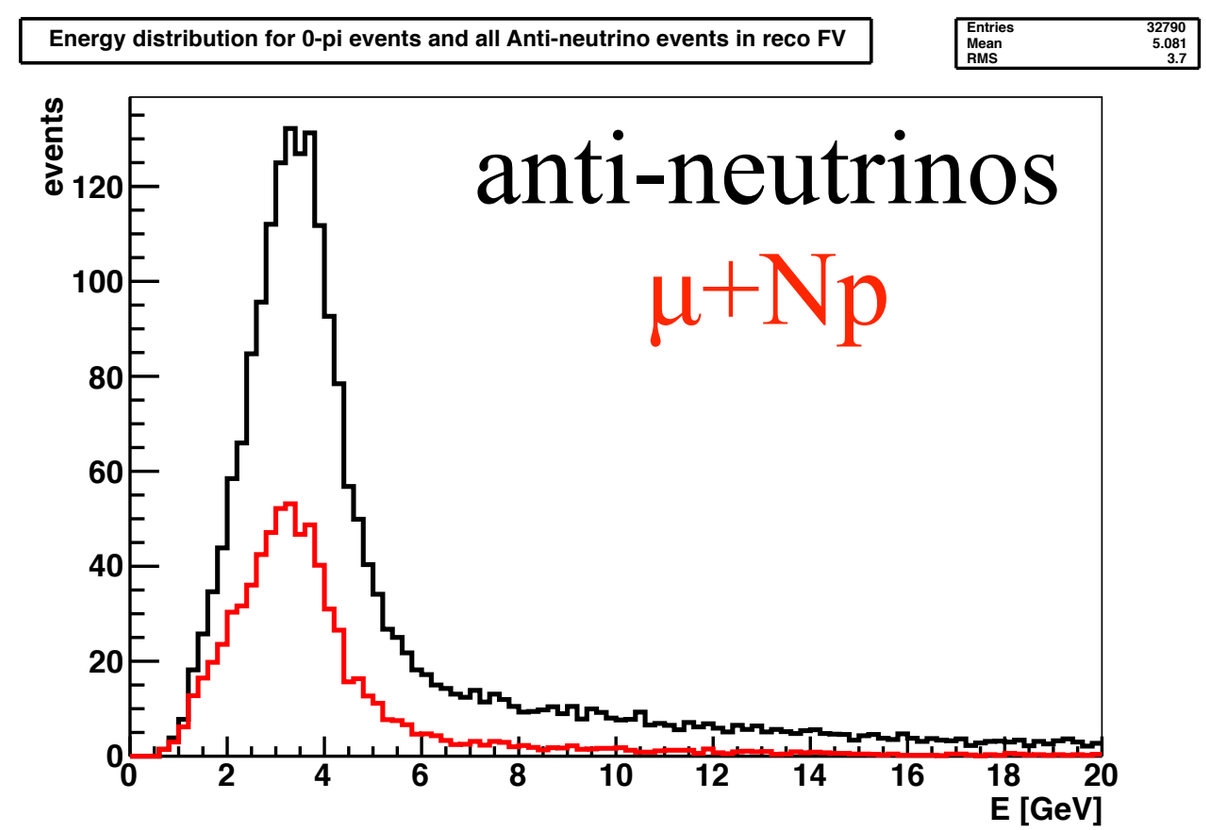
Identified as	Proton	Kaon	Pion	Muon
Proton	0.97	0.15	0.05	0
Kaon	0.03	0.60	0.09	0.01
Pion	0	0.06	0.25	0.28
Muon	0	0.20	0.61	0.71

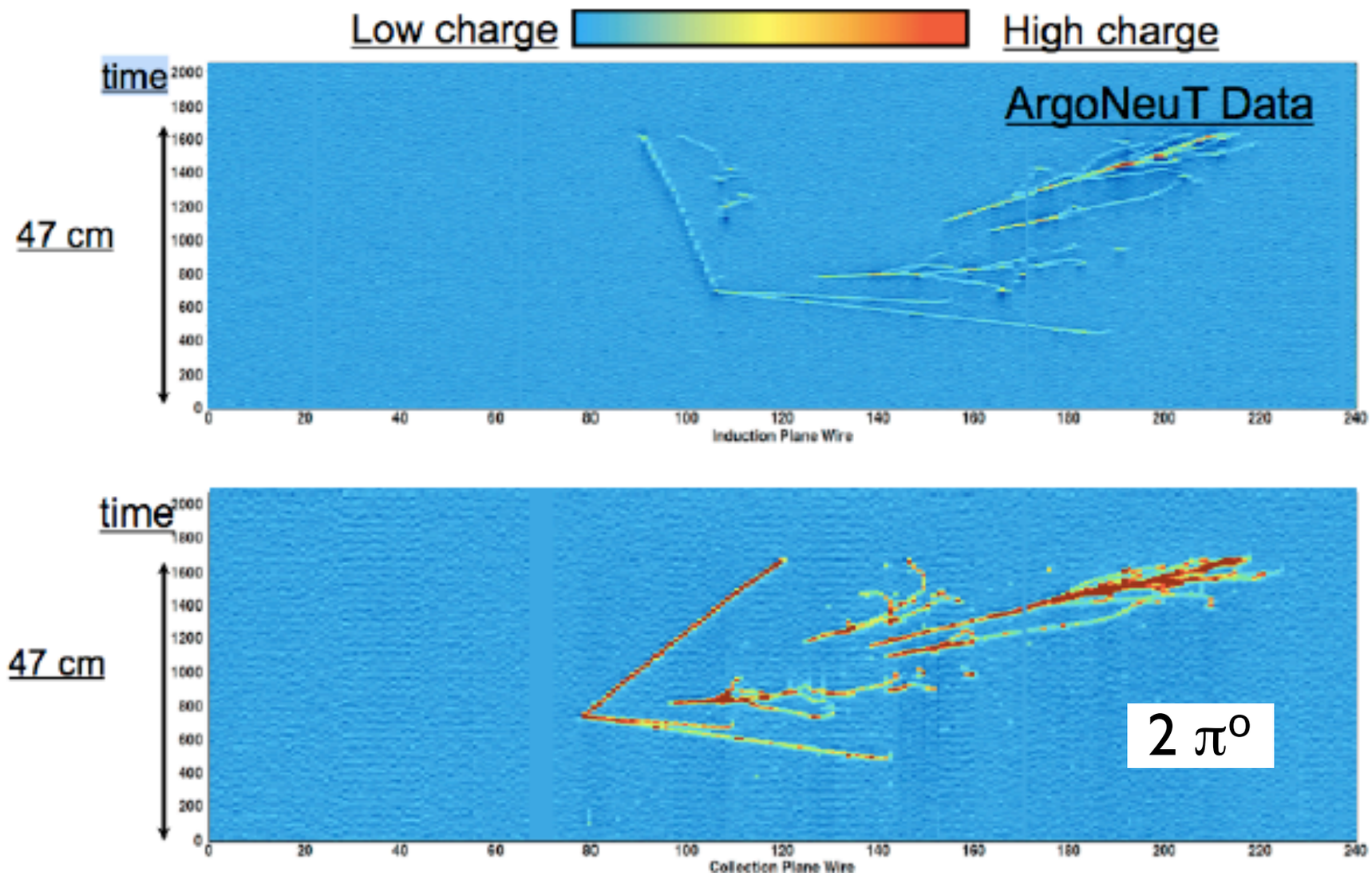
ArgoNeuT

Energy spectrum in anti-neutrino mode

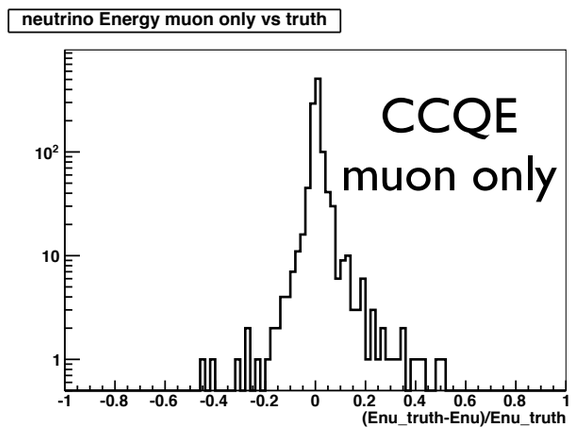


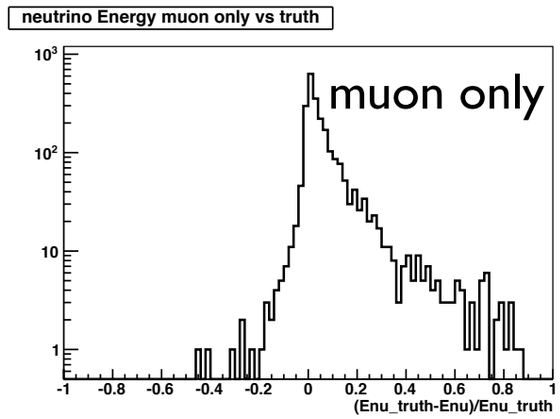




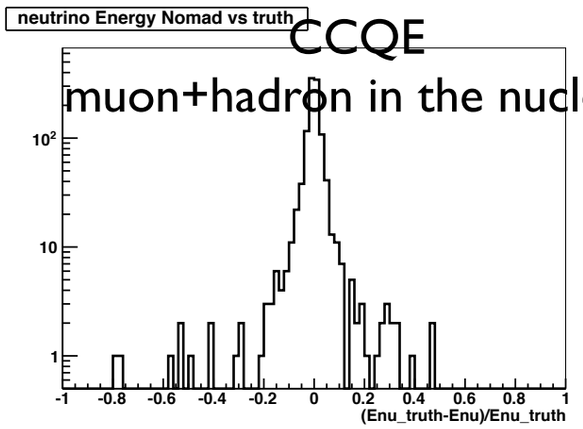

Low charge
High charge
time
47 cm
ArgoNeuT Data
Induction Plane Wire
time
47 cm
2 π°
Collection Plane Wire

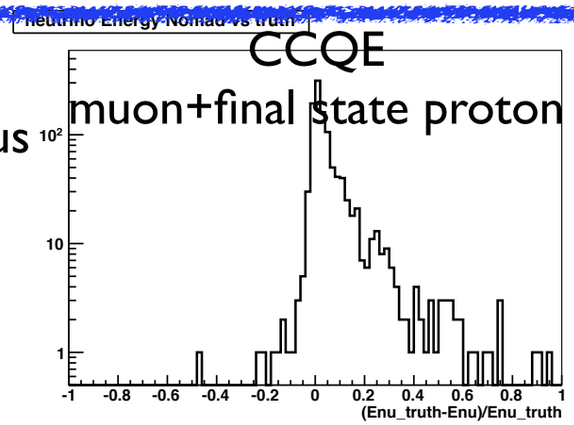
Energy reconstruction: (Enu_truth-Enu)/Enu_truth

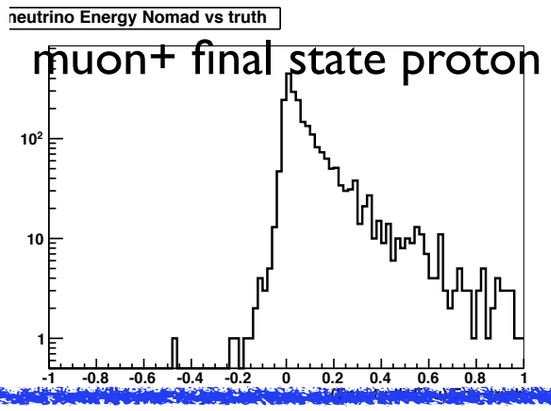




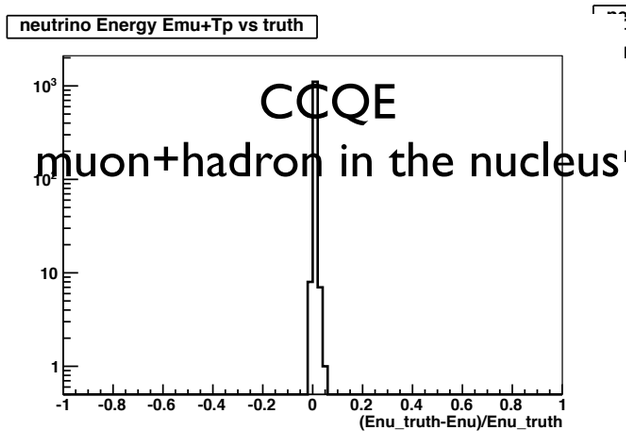
1) muon only

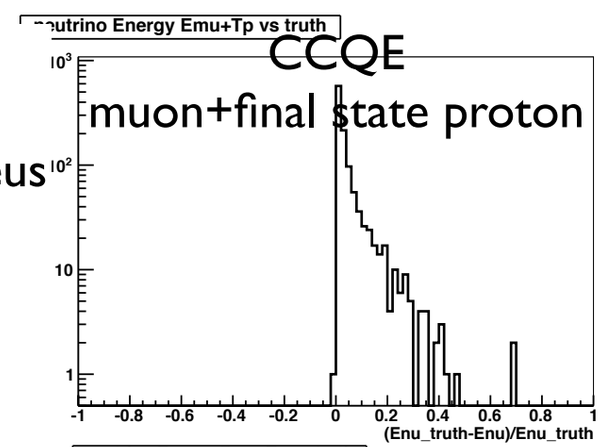


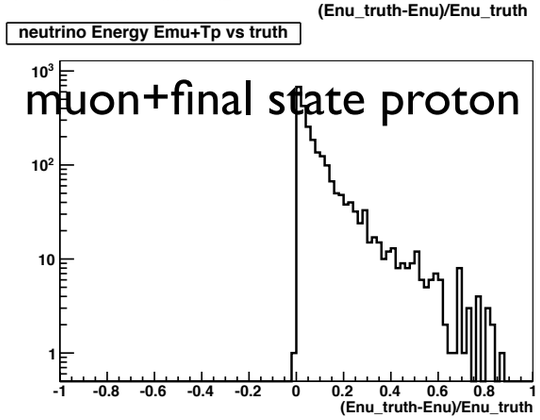




2) Nomad







3) Energy conservation

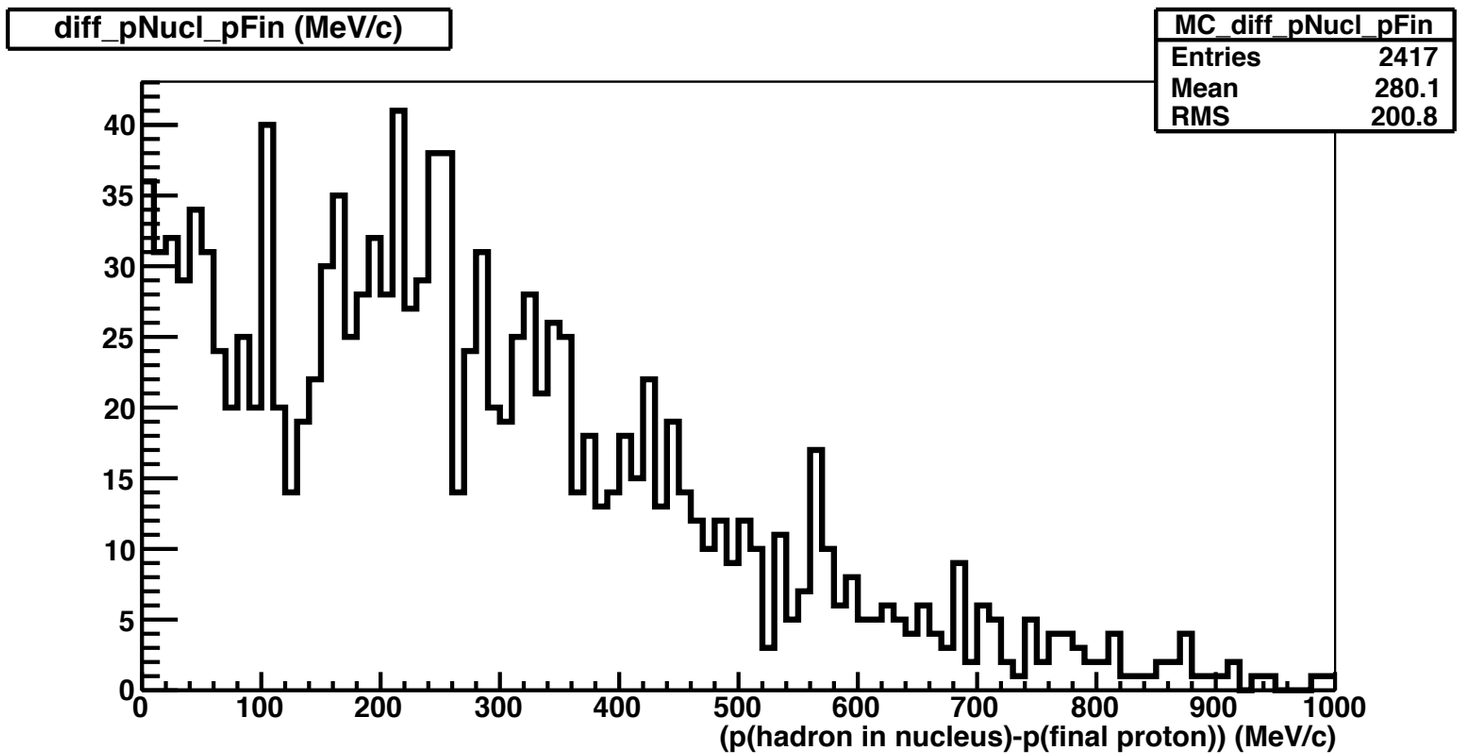
μ^-p final state events

anti-nu mode

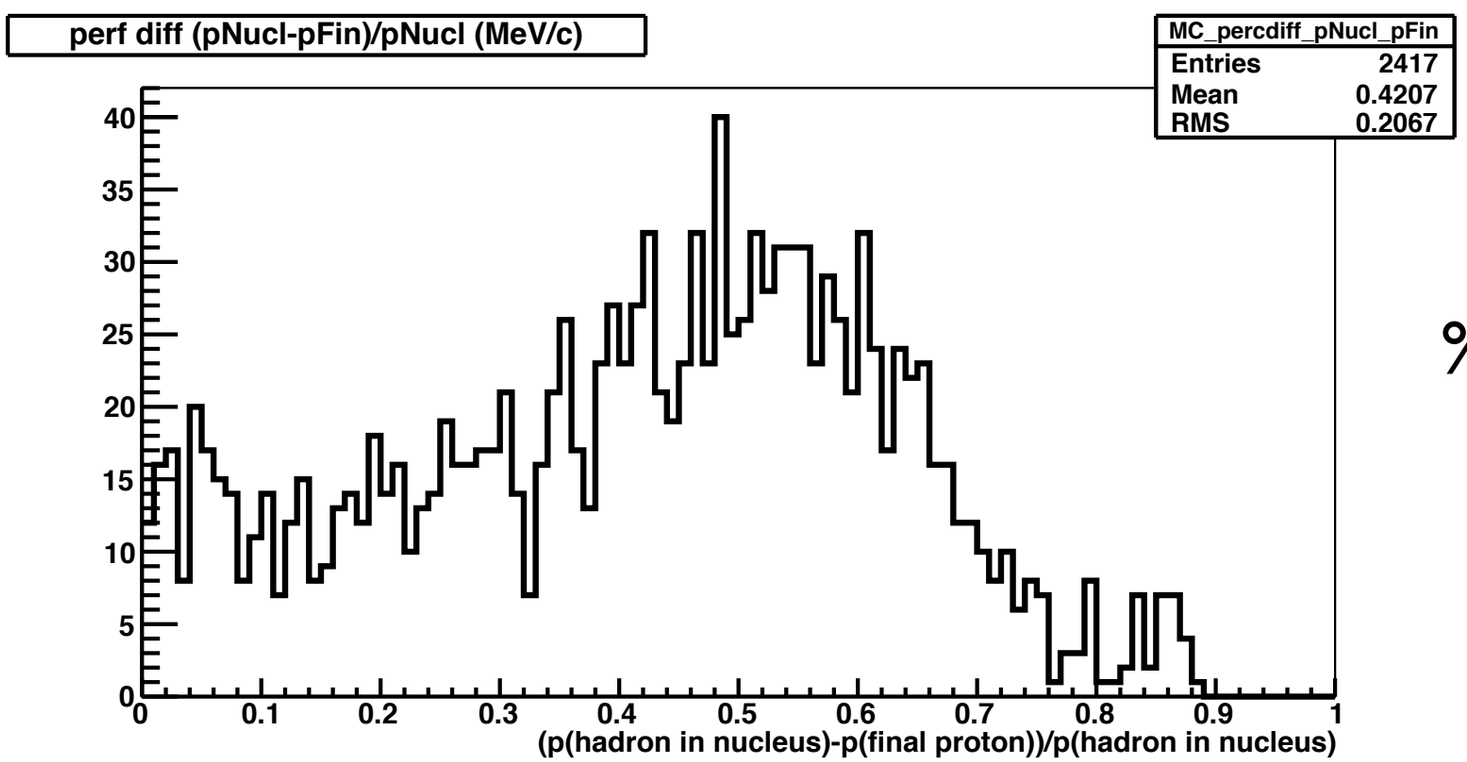
μ^-p final state events

anti-nu mode

Effect of FSI



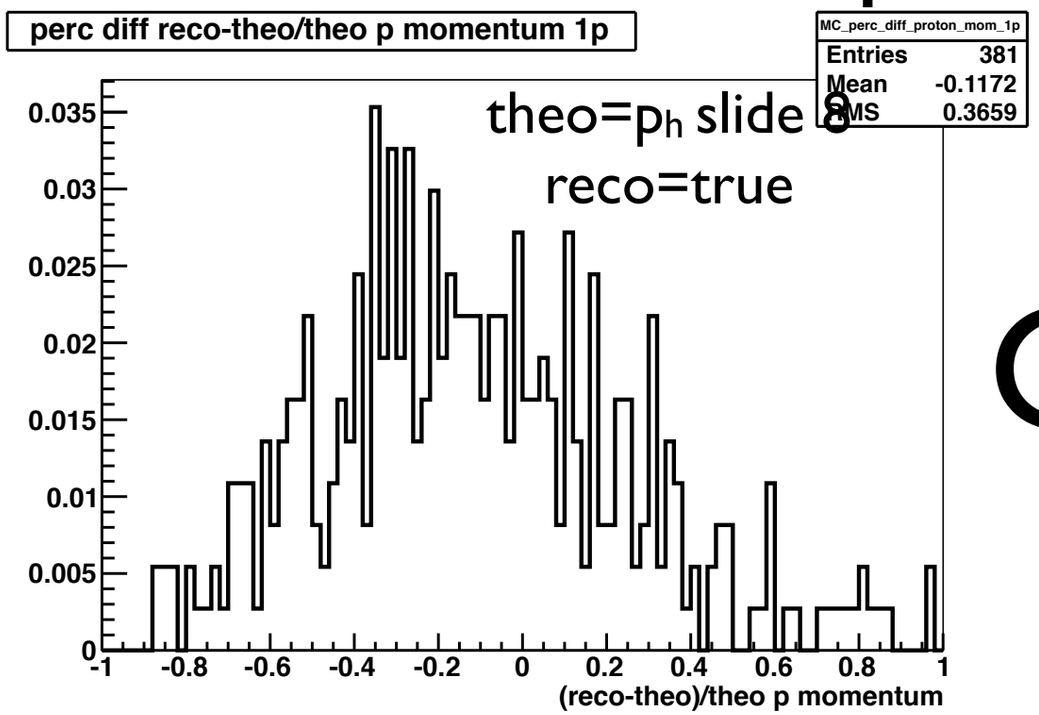
Difference in momentum
between
the proton in the nucleus
and
the final state proton

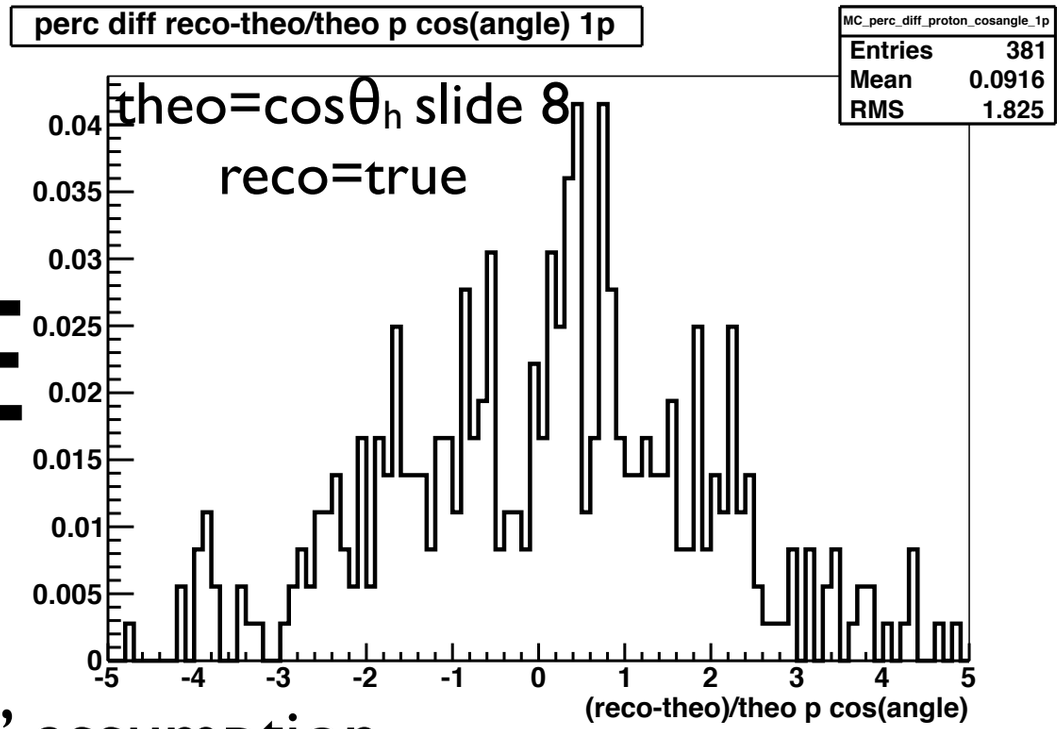


% difference

μ^-p events
anti-nu mode

Difference between reconstructed and "predicted" proton kinematics

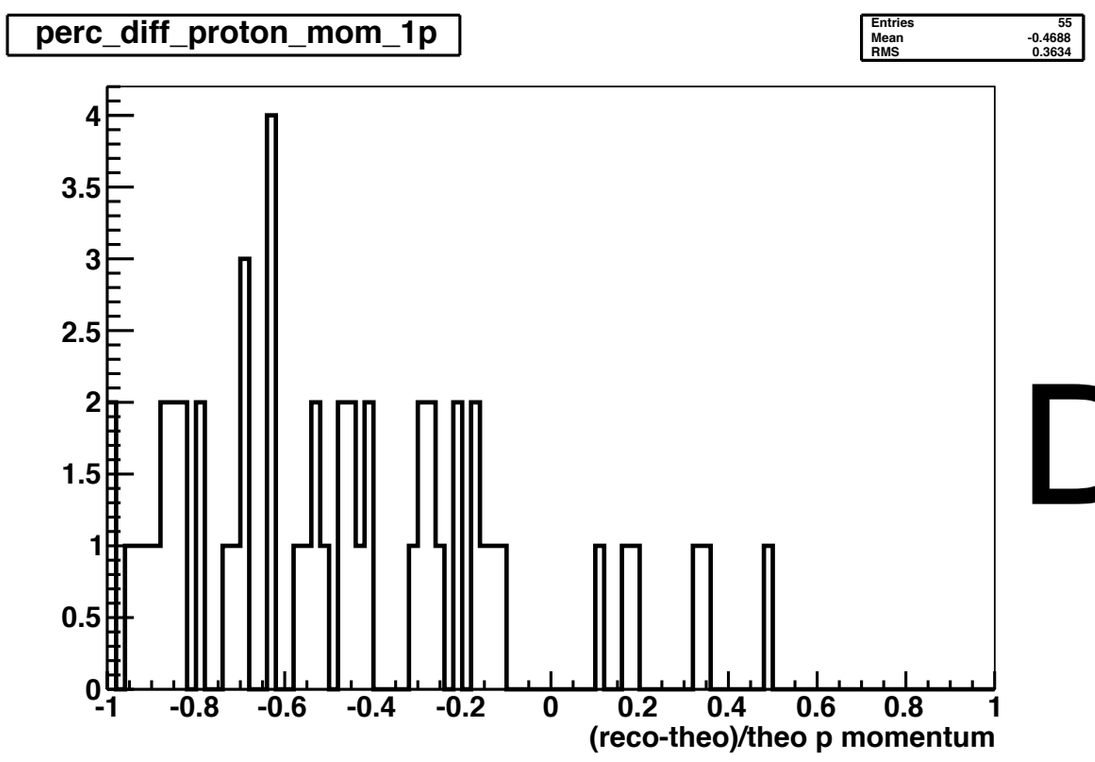




GENIE

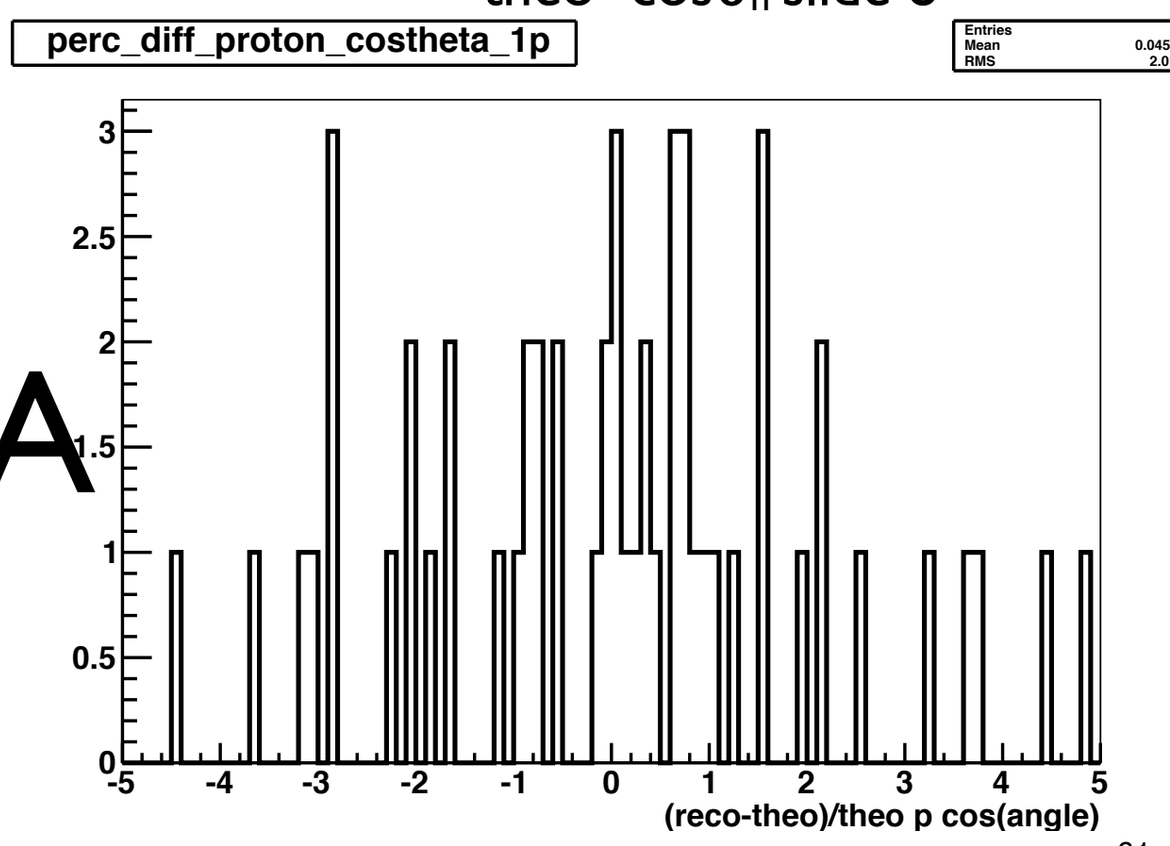
"QE on nucleon at rest" assumption is not good!

theo=p_h slide 8



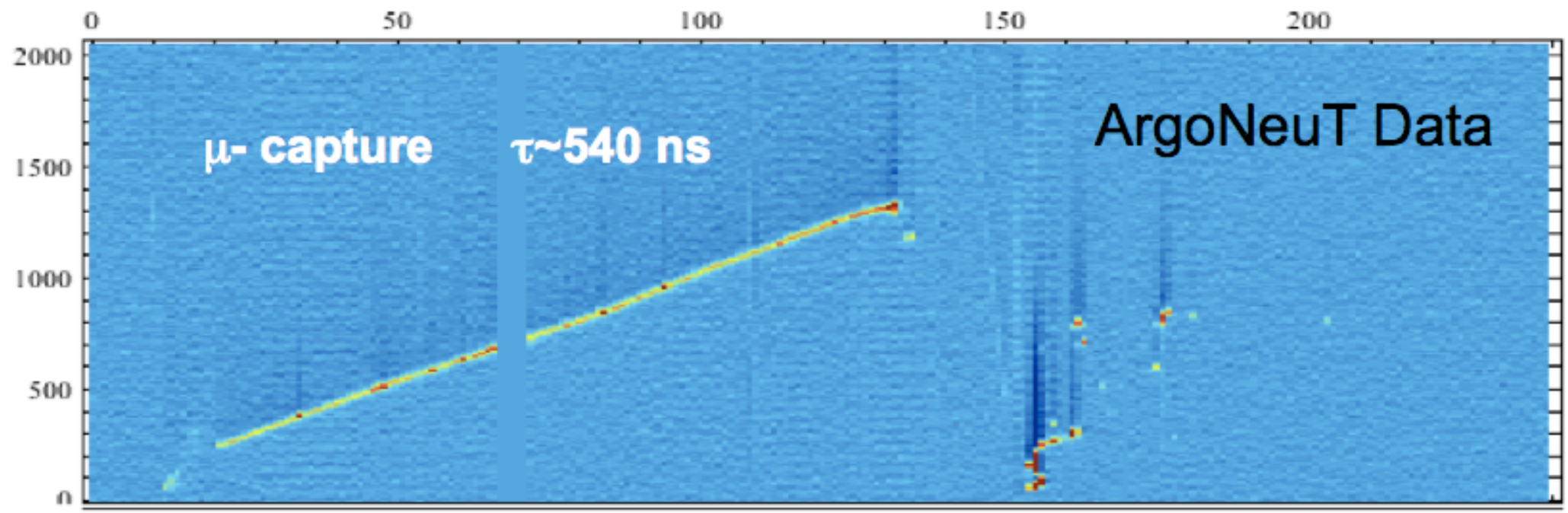
DATA

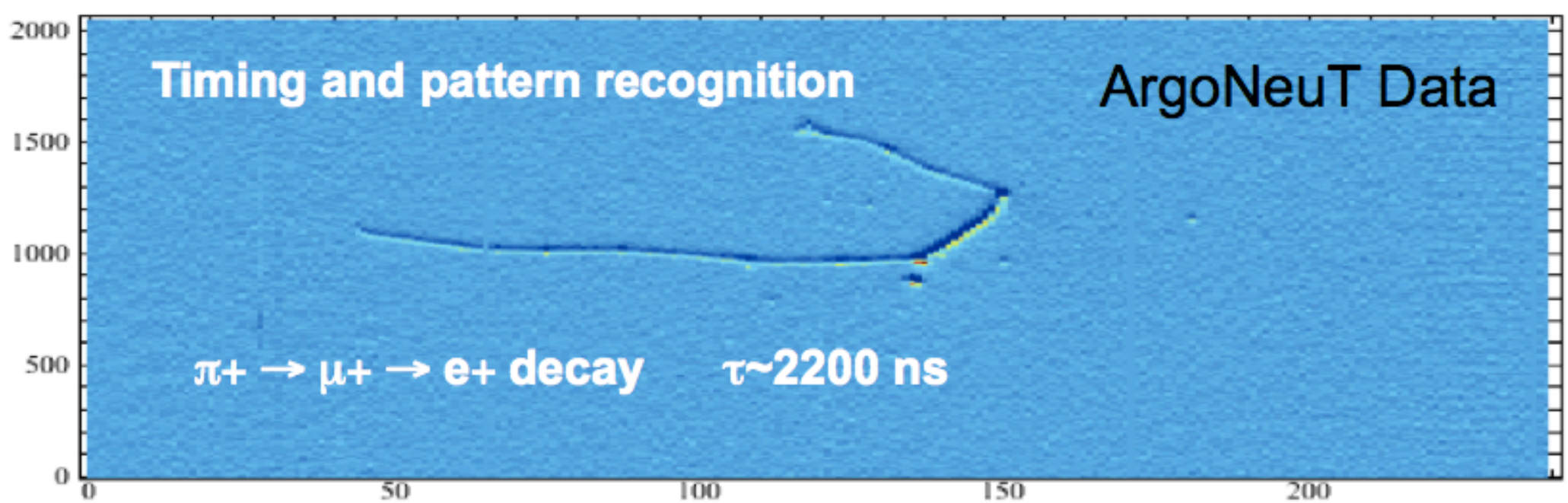
theo=$\cos\theta_h$ slide 8

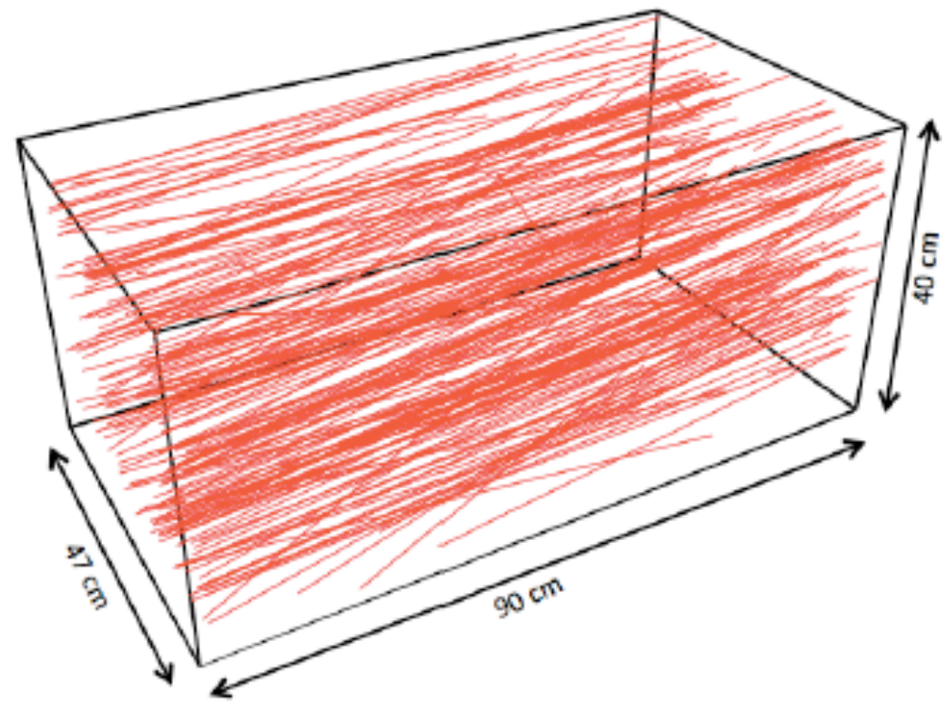
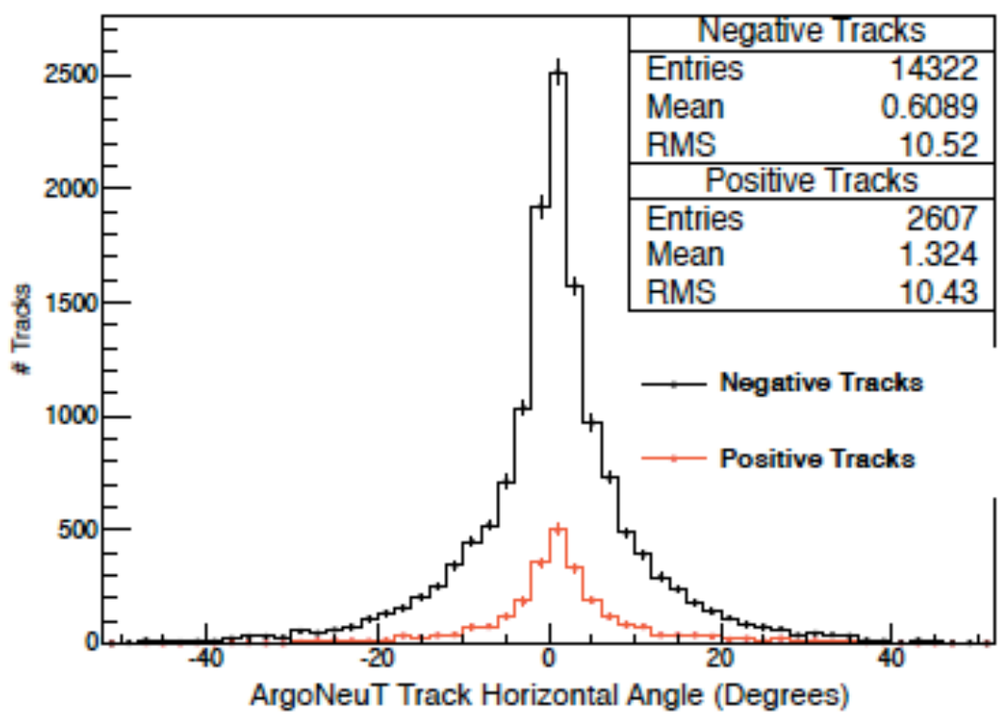
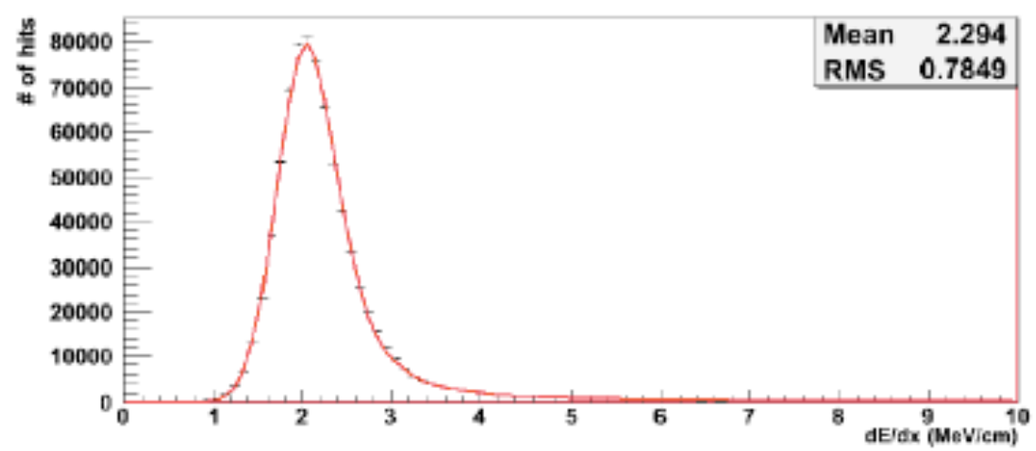


Particle Identification

Muon sign determination





Calorimetry on Through-going Muons

- Calorimetry tested on through going muons.
- The final sample contains 14322 μ^- and 2607 μ^+.
- C.Anderson et al., arxiv.org:1205.6702, accepted by JINST