Reconstruction Algorithms for Electron Neutrino Appearance in NOvA

Evan Niner

For the NOvA Collaboration

Indiana University

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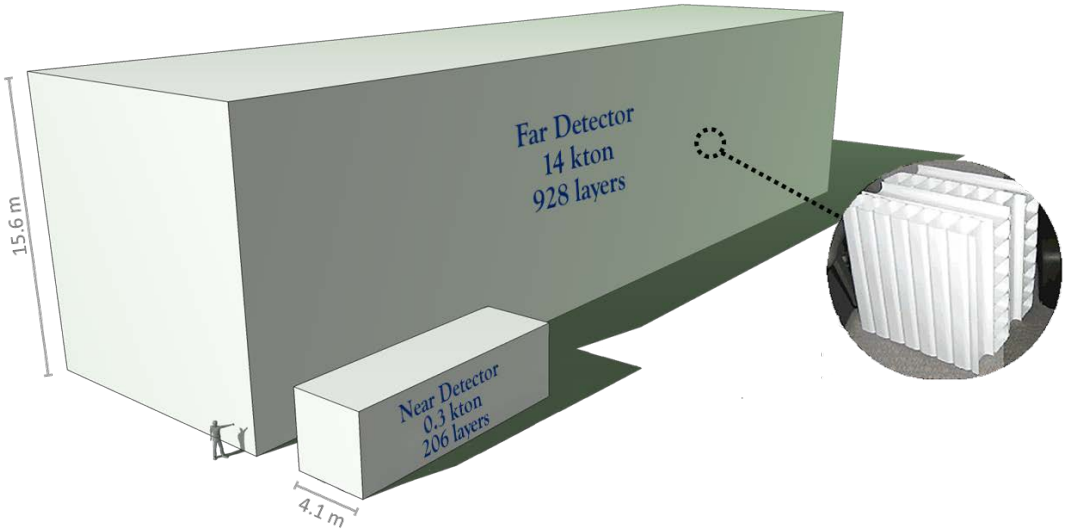
NOvA Overview

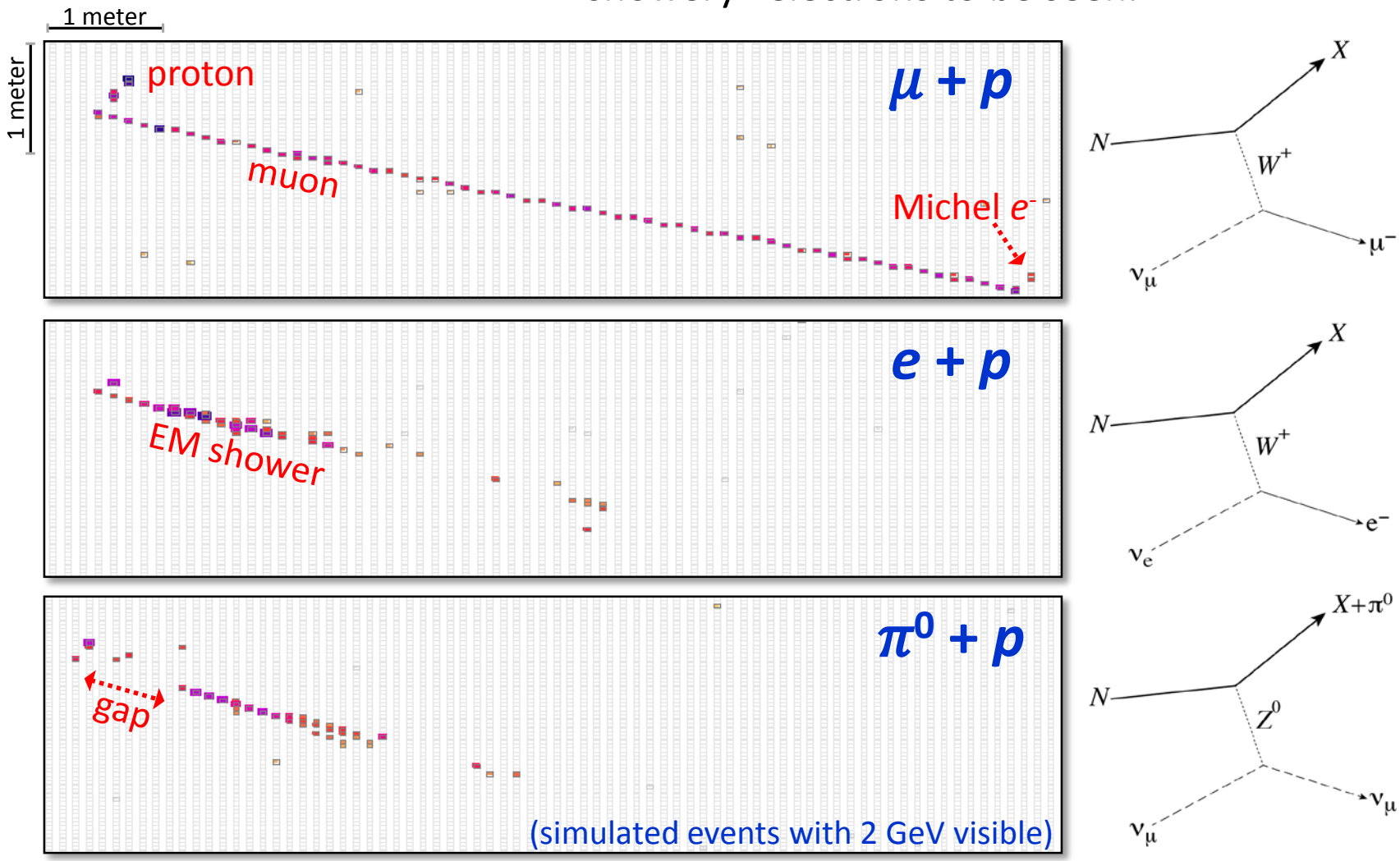


- A long baseline neutrino oscillation experiment currently under construction.
- NOvA uses a Near Detector at FNAL and a Far Detector located 810 kilometers away in Ash River, MN placed 14 milliradians off-axis from the existing NuMI beam.
- The experiment will probe the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation channels to achieve a wide range of physics goals.
- For a more detailed overview see the following talk by Satish Desai.

- Functionally identical Near and Far Detectors consist of extruded pvc cells filled with liquid scintillator.
- Each cell contains a wavelength shifting fiber connected to an Avalanche Photo Diode (APD).
- Planes of horizontal and vertical cells are alternated to provide 3D tracking.

Events in NOvA

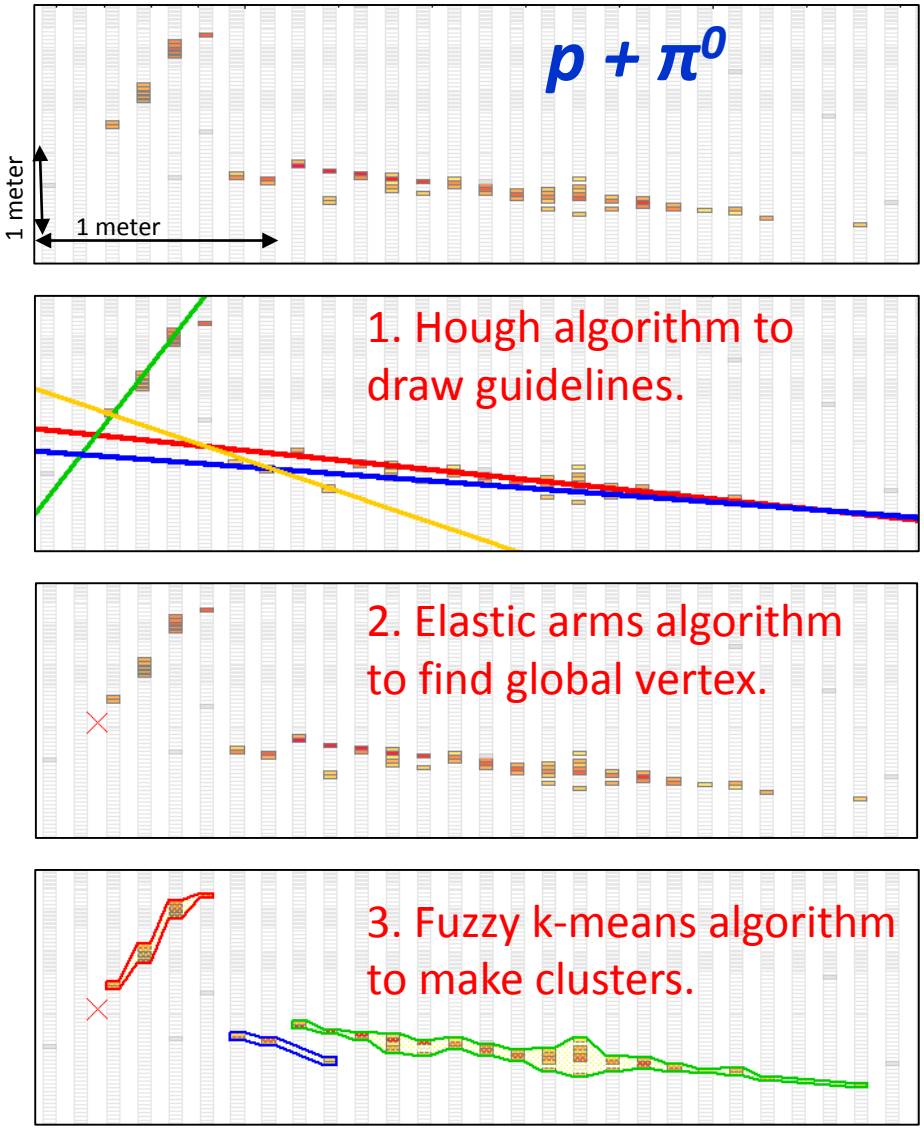
The fine detector segmentation and low-Z allow for differences between "tracky" muons and "showery" electrons to be seen.



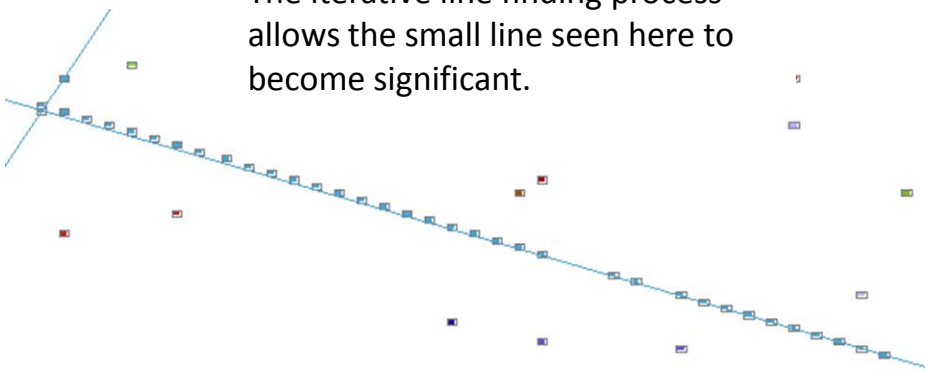
1 radiation length = 38cm (6 cell depths, 10 cell widths)

Global Reconstruction Philosophy

- Find general event features before applying finer reconstruction.
- Knowing the vertex makes short tracks more significant.
- Approach is robust against uninstrumented gaps in the detector.

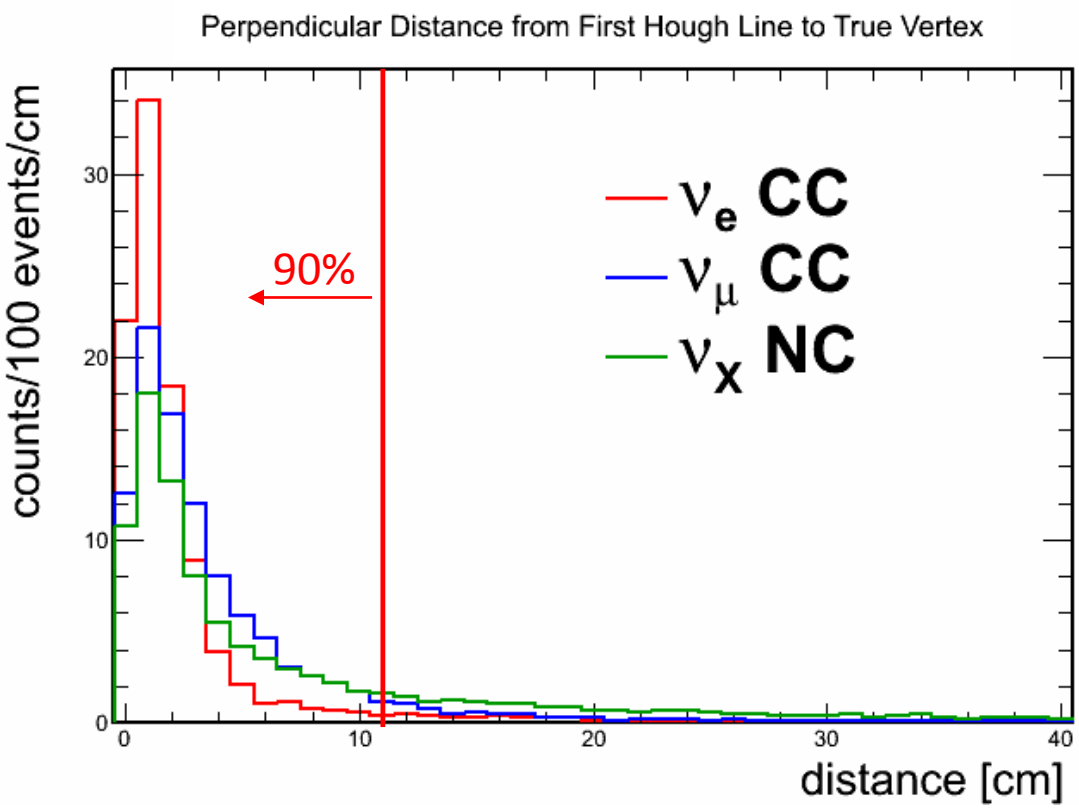


Multi-Hough Transform: Building Guidelines



The iterative line finding process allows the small line seen here to become significant.

- Modified algorithm where pairs of points are mapped into hough space, more robust against noise.
- Points near lines are removed in an iterative process in order to find finer structure.
- In 90 % of all charged current events the prominent hough line comes within 11 cm of the event vertex.



Fernandes & Oliveira, Pattern Recognition 41 (2008) 299-314

Elastic Arms: Vertex Finding

- The algorithm fits a model of a single vertex and N "arms" to the event by minimizing the energy function below.

Least squares | Noise penalty | Displaced prong penalty

hits → K, arms → N

$$E = \sum_{i=1}^{K}\sum_{a=1}^{N} V_{ia} M_{ia} + \lambda \sum_{i=1}^{K}\left(\sum_{a=1}^{N} V_{ia} - 1\right)^2 + \frac{2}{\lambda_v}\sum_{a=1}^{N} D_a$$

Distance from vertex to first hit in prong

Association strength of hit i to arm a

$\mathbf{X}^2$ distance from hit i to arm a

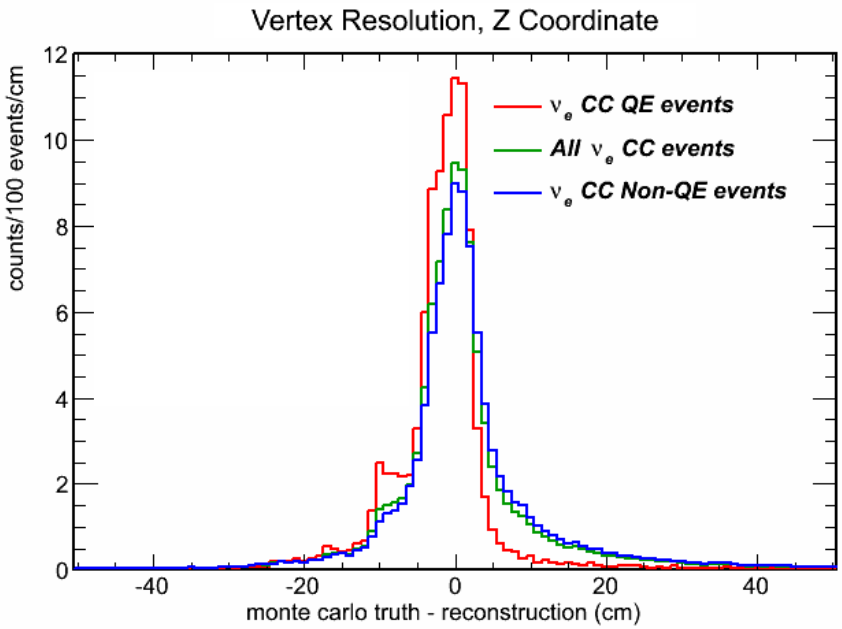
Photon conversion distance scale

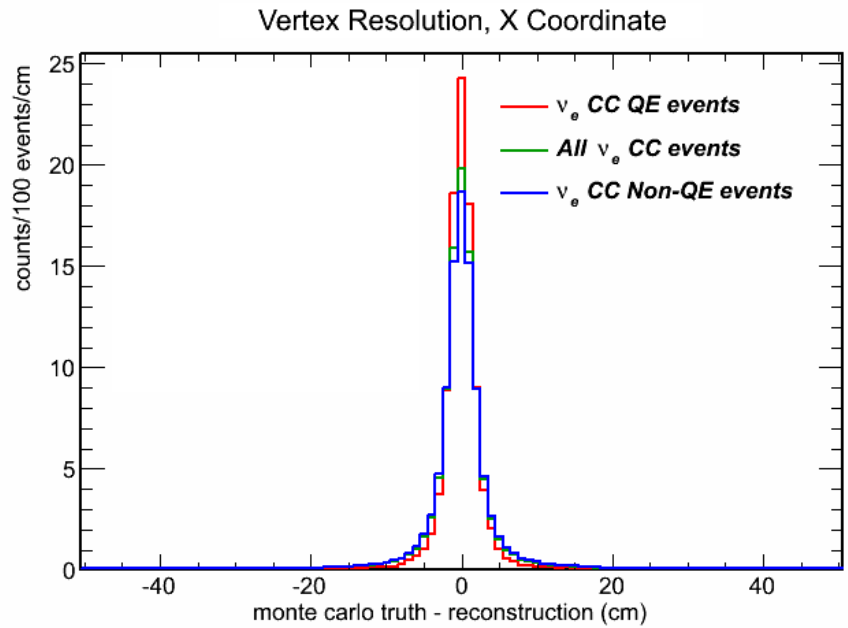
- Hough lines and intersections are used as seeds for arms and vertex.
- This is unique application because the vertex location is not known a priori.
- Events in NOvA tend to be simple 2-5 track events and interactions are rare enough to be successfully separated into separate slices.

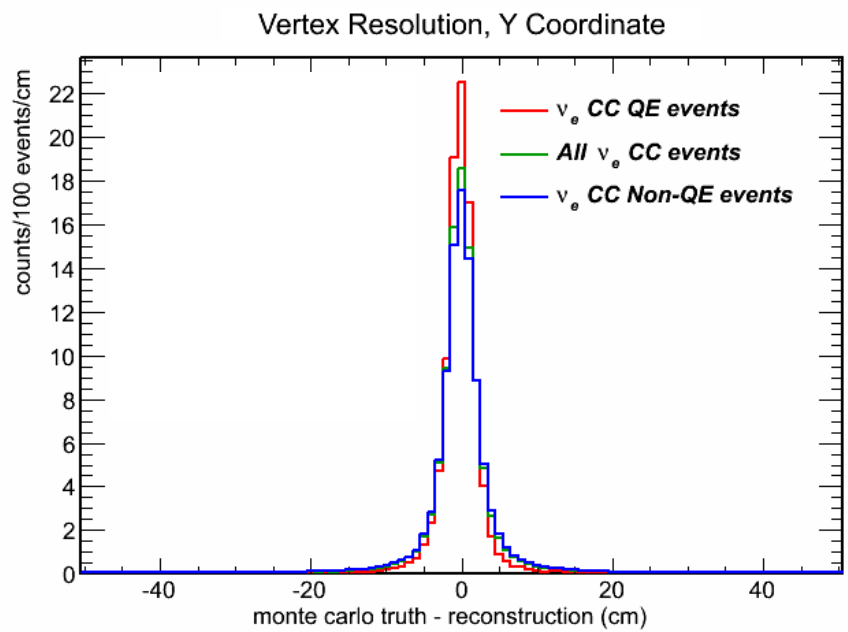
M. Gyulassy and M. Harlander, Computer Physics Communications, 66 (1991) 32-46.
M. Ohlsson, C. Peterson, Computer Physics Communications, 71 (1992) 77-98.
M. Ohlsson, Computer Physics Communications, 77 (1993) 19-32.
R. Fruwirth and A. Strandie, Computer Physics Communications, 120 (1999) 197-214.

Vertexing Performance

Far Detector Simulation

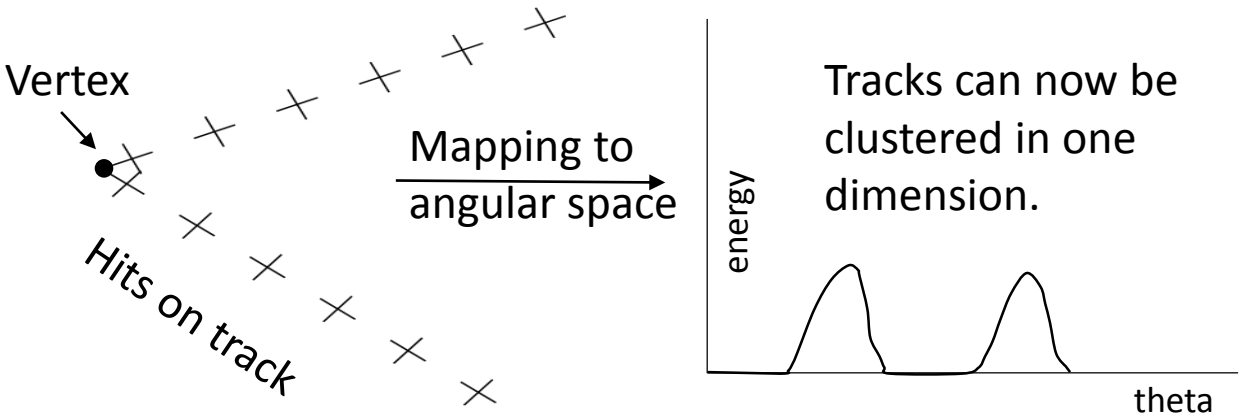






The vertex resolution for all ν_e cc events is less than 5cm (one cell) in X and Y, and 8 cm in Z.

Possibilistic Fuzzy K-Means Clustering



Tracks can now be clustered in one dimension.

Distance to cluster centers

$$d_{ij} = \left(\frac{\theta_j - \bar{\theta}_i}{\sigma_j}\right)^2$$

Cell hit j

Cluster center i

Angular uncertainty, derived from simulation

- Individual hits are allowed to have membership in multiple clusters, making them "fuzzy".
- A cells total membership cannot exceed one, but it is not normalized, allowing noise hits to be unclustered.
- Clustering is done separately in each view of the detector and then matches are made based on cluster characteristics.

Cluster Membership

$$U_{ij} = e^{-\frac{m\sqrt{c}d_{ij}}{\beta}}$$

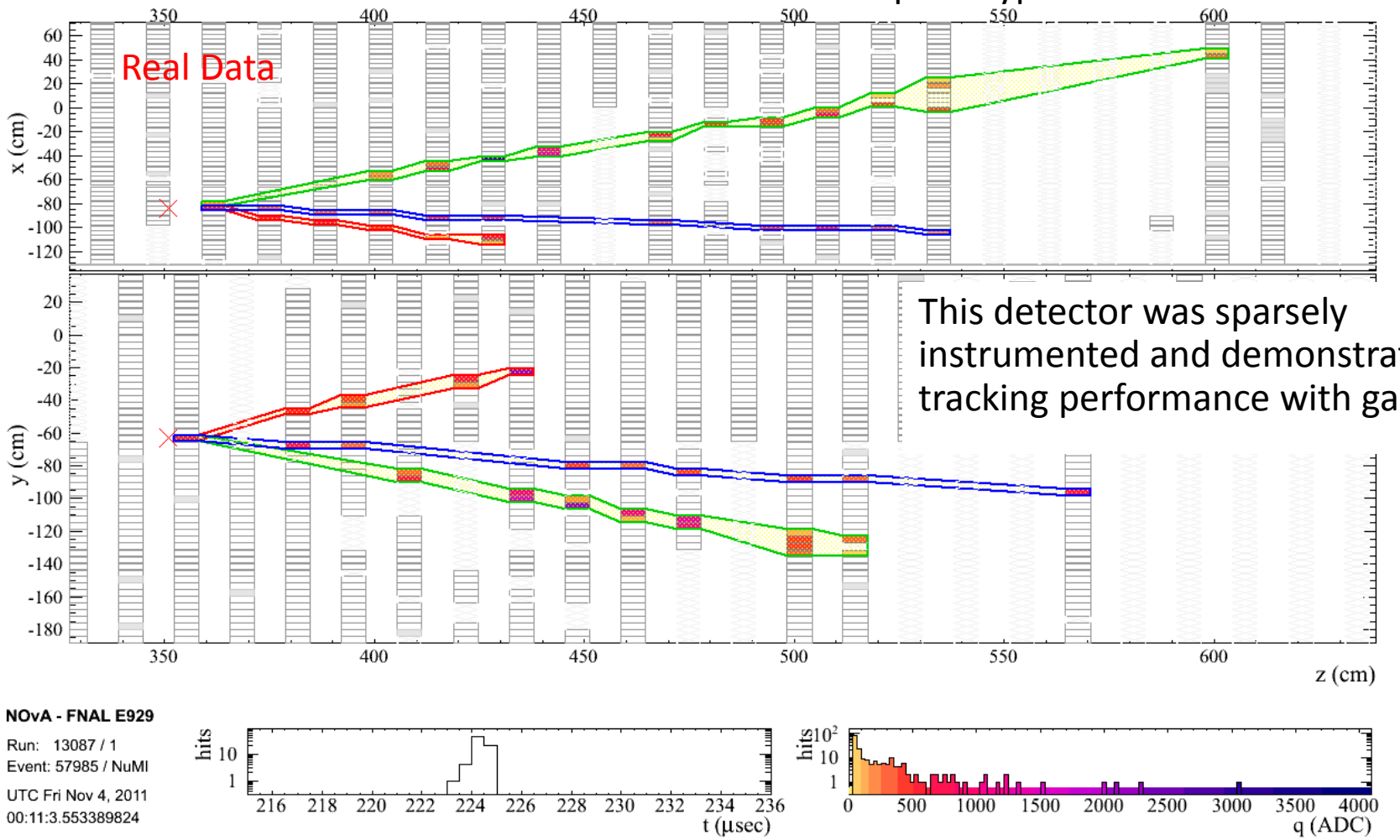
Updating cluster centers

$$\bar{\theta}_i' = \bar{\theta}_i + \frac{\sum_{j=1}^{K} \frac{U_{ij}^m}{\sigma_j^2}\left(\theta_j - \bar{\theta}_i\right)}{\sum_{j=1}^{K} \frac{U_{ij}^m}{\sigma_j^2}}$$

R. Krishnapuram, J.M. Keller, A possibilistic approach to clustering, IEEE Trans. Fuzzy Syst. 1 (1993) 98110.
M.-S. Yang, K.-L. Wu, Unsupervised possibilistic clustering, Pattern Recognition, 39 (2006), pp. 521.

Algorithm Performance

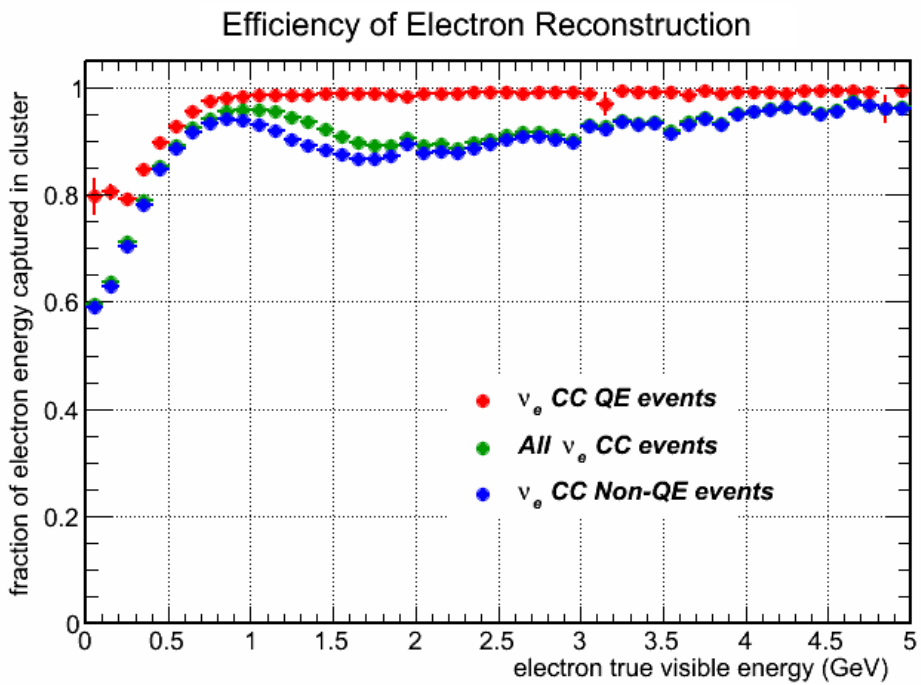
A well reconstructed multi-prong event with a π^0 candidate found during operation of the Near Detector on the Surface (NDOS) prototype detector at FNAL.

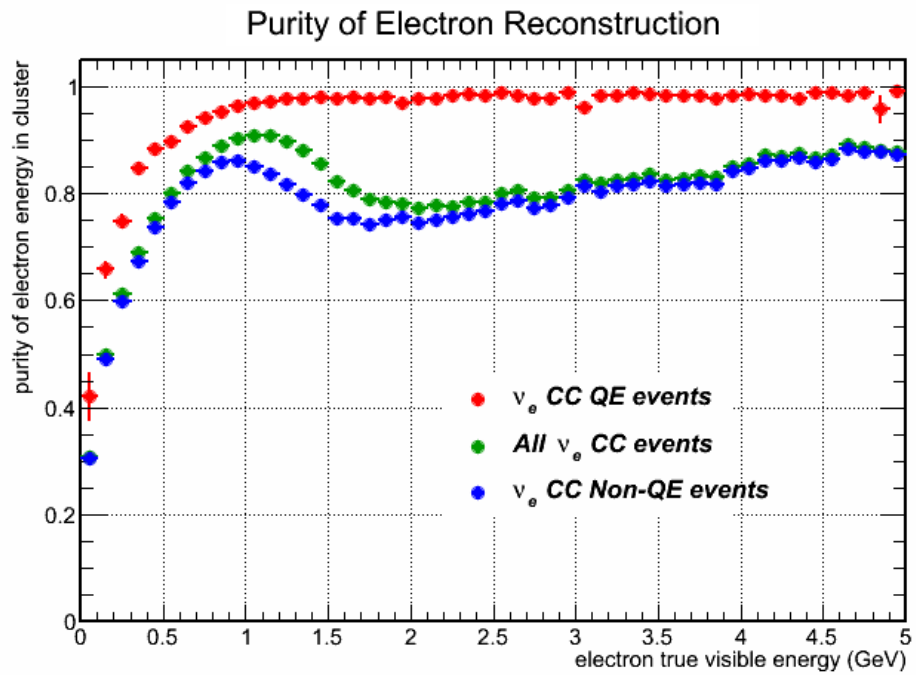


This detector was sparsely instrumented and demonstrates tracking performance with gaps.

Clustering Performance

Far Detector Simulation





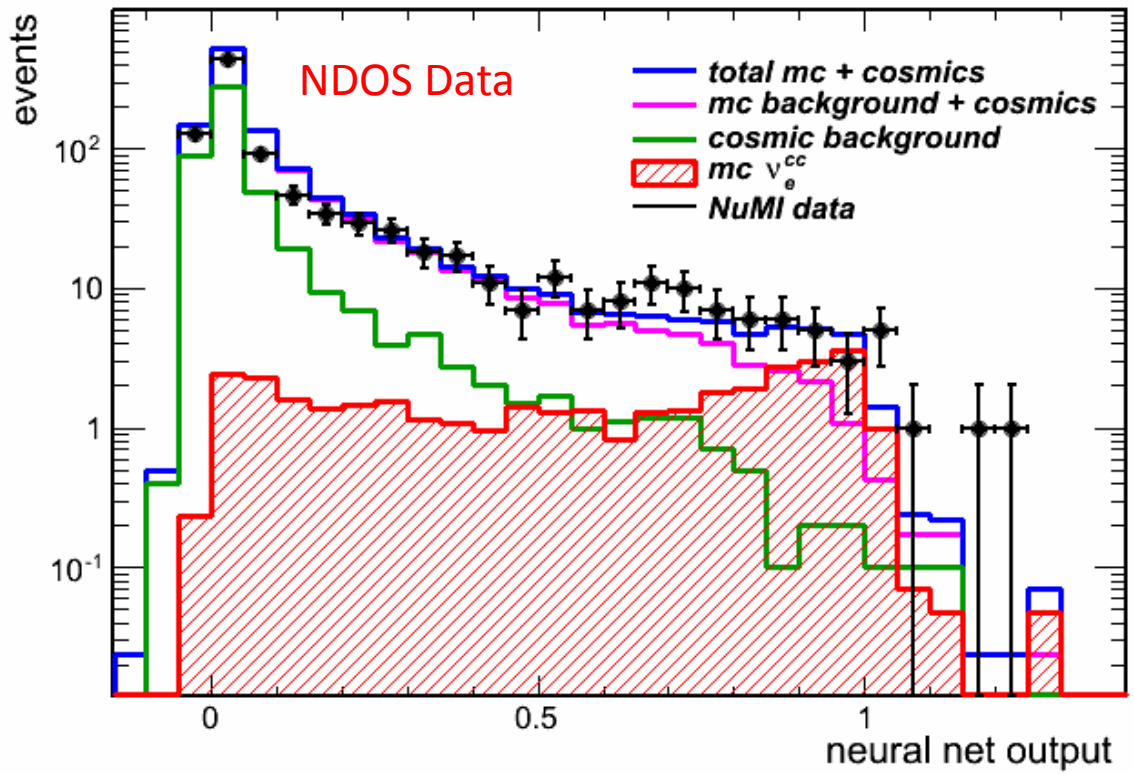
Achieves >90% efficiency and >80% purity at energies of interest in reconstructing a cluster capturing the primary electron in a charged current interaction.

$$\text{Efficiency} = \frac{\text{electron energy in cluster}}{\text{electron energy in event}} \qquad \text{Purity} = \frac{\text{electron energy in cluster}}{\text{total energy in cluster}}$$

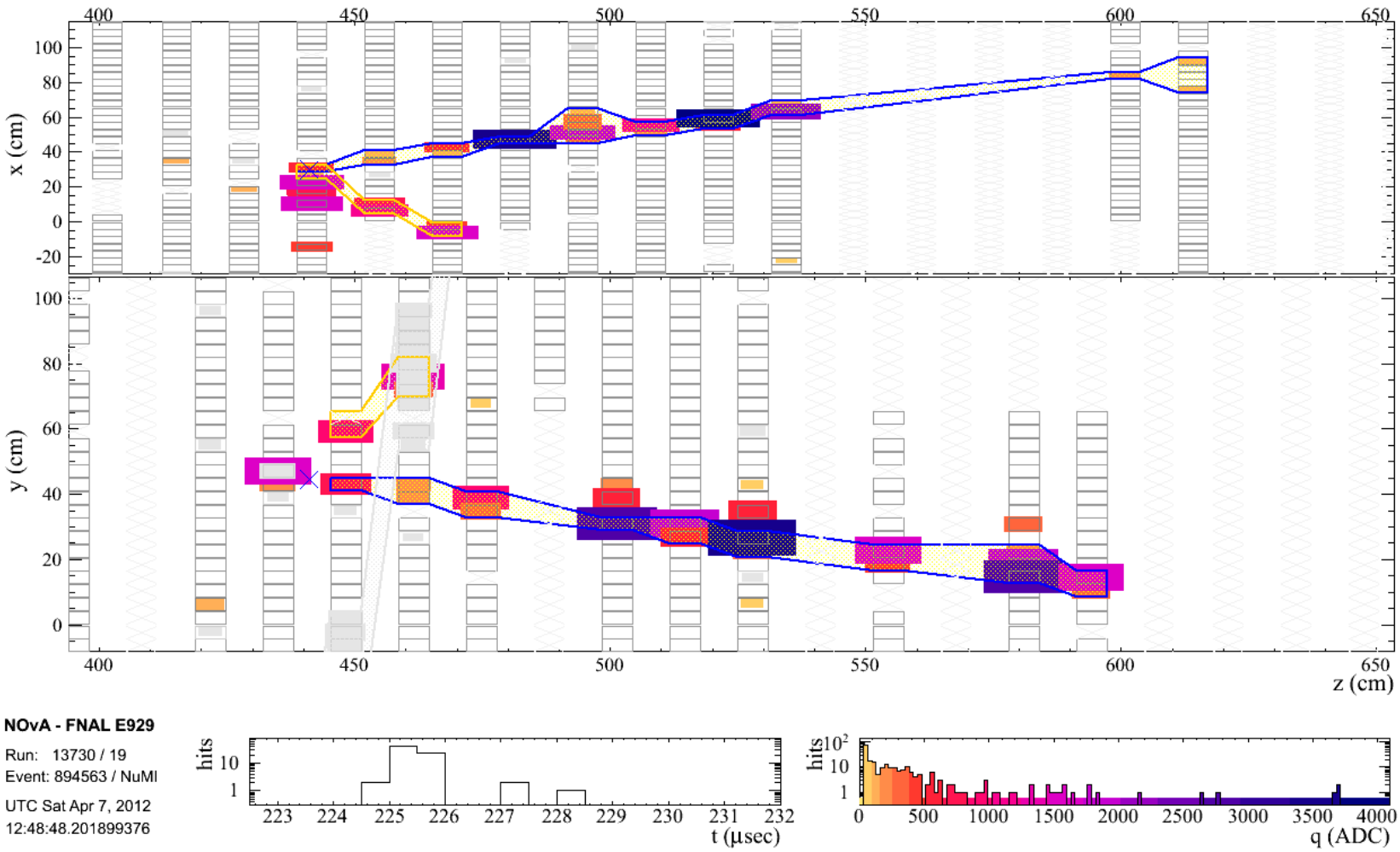
Electron Neutrinos in NDOS

- The full analysis framework using this reconstruction chain as input to a neural net was run over six months of NuMI data collected at NDOS.
- This is the first test that the planned Far Detector analysis works on real data.

- This reconstruction chain is the input for a neural net that is one of the primary frameworks for the oscillation analysis. For sensitivity studies of the planned ν_e appearance analysis see the talk by Chris Backhouse.
- The data, in black, pulls away from the predicted background plus cosmic spectrum in magenta, indicating the presence of ν_e charged current events.

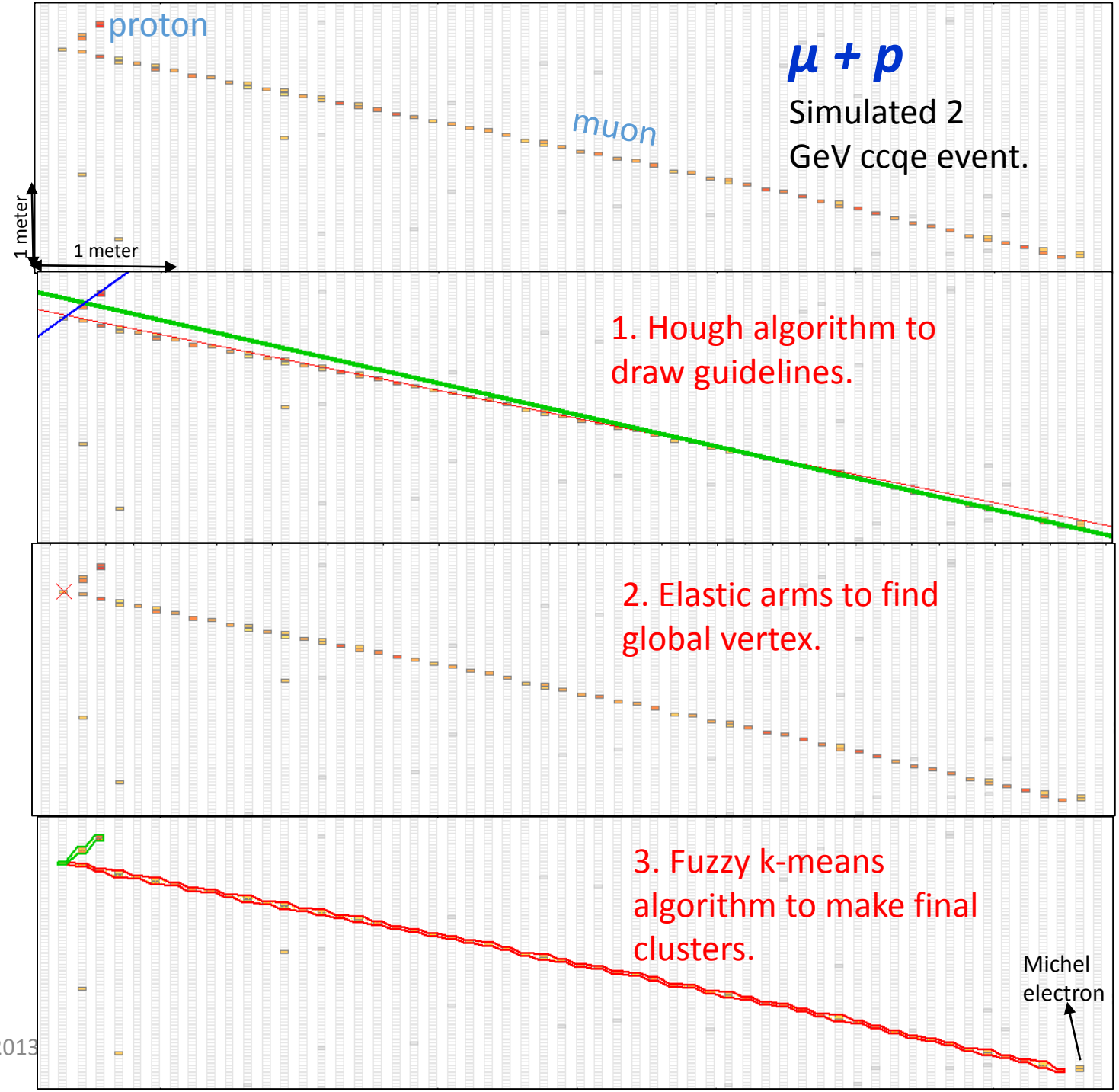


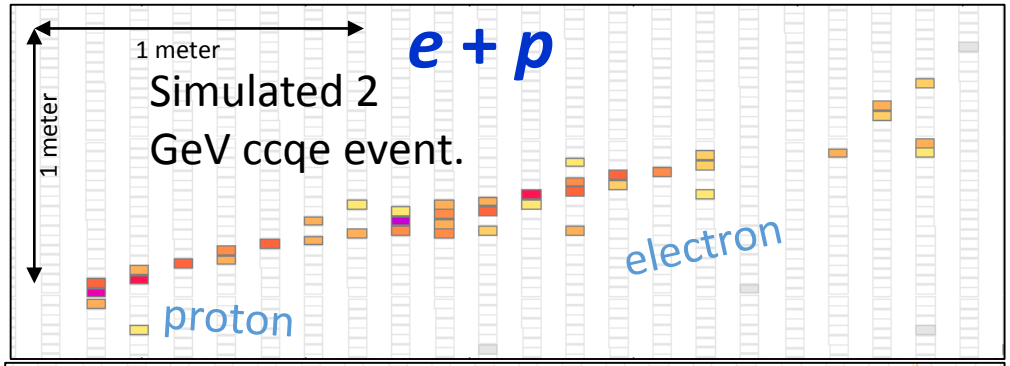
ν_e candidate in NDOS data



Conclusions

- The reconstruction techniques described have proved to be a good approach to event vertexing and have good performance with both track-like and shower-like particles.
- This reconstruction lays the framework for one of the principle particle identification algorithms being developed for the electron neutrino appearance analysis.
- The analysis has been shown to function on real data in the NOvA prototype detector.


proton
muon
μ + p
Simulated 2 GeV ccqe event.
1 meter
1 meter
1. Hough algorithm to draw guidelines.
2. Elastic arms to find global vertex.
3. Fuzzy k-means algorithm to make final clusters.
Michel electron


1 meter
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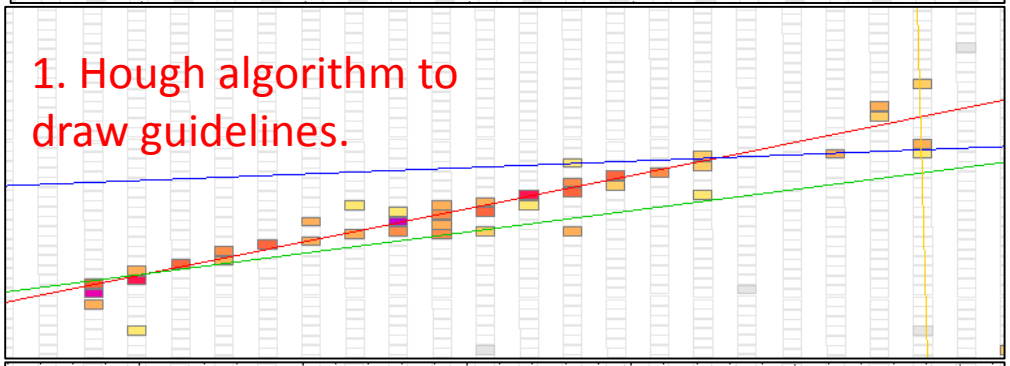
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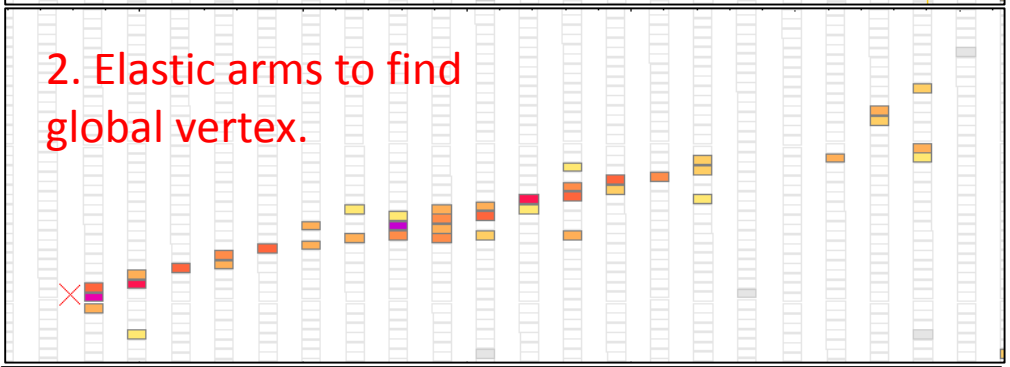
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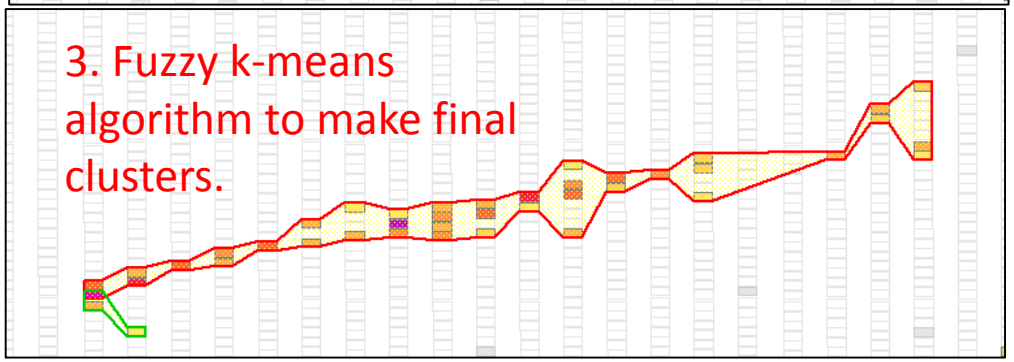
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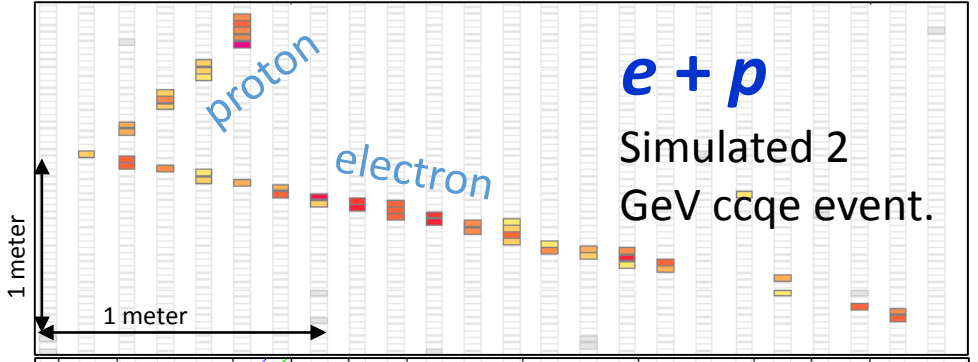
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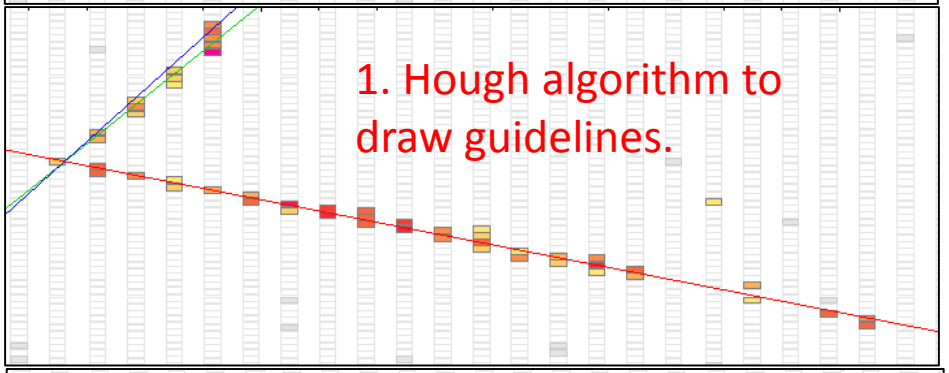
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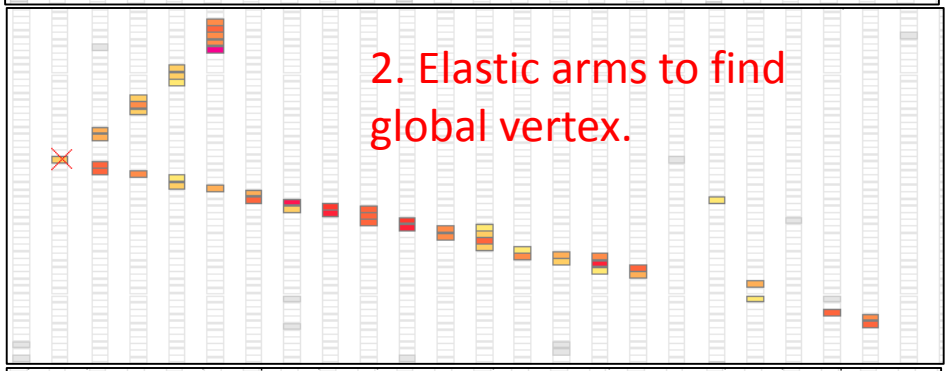
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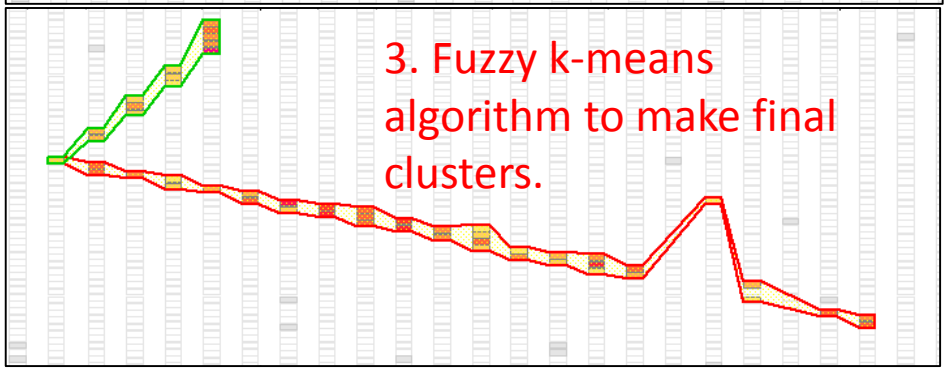
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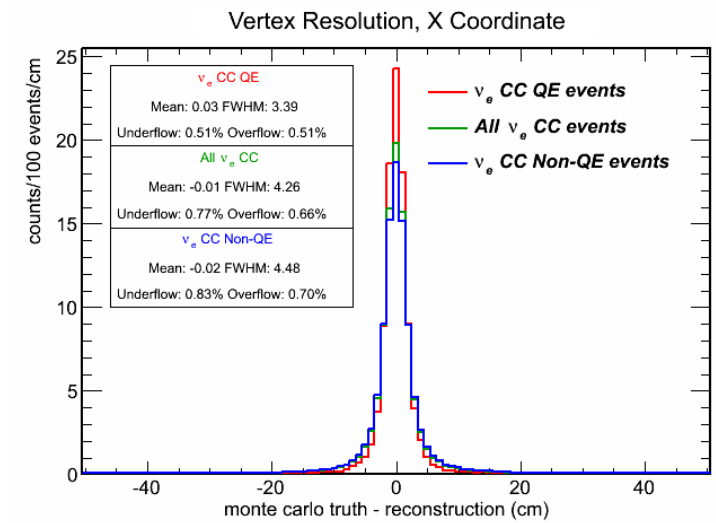
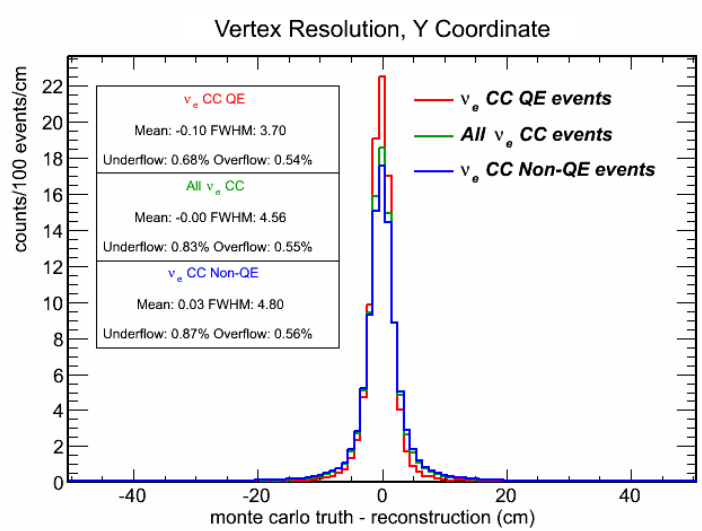
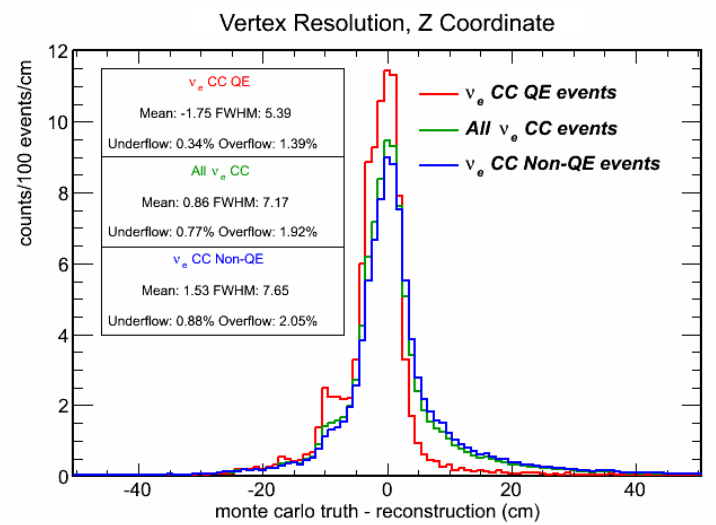
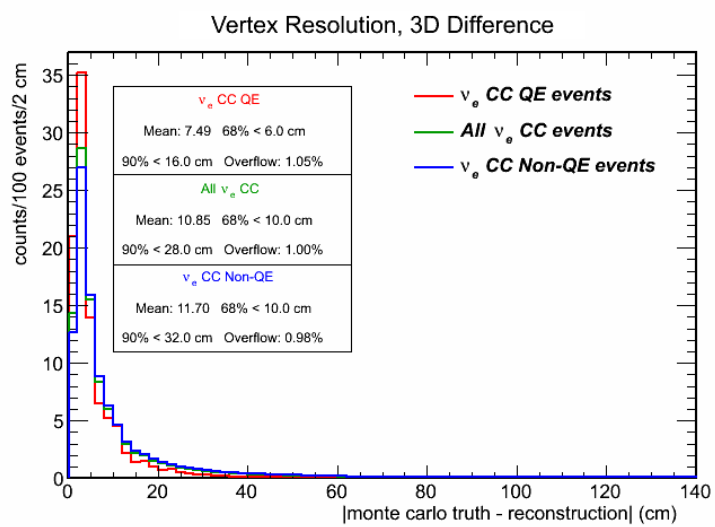
Vertexing Performance

Far Detector Simulation









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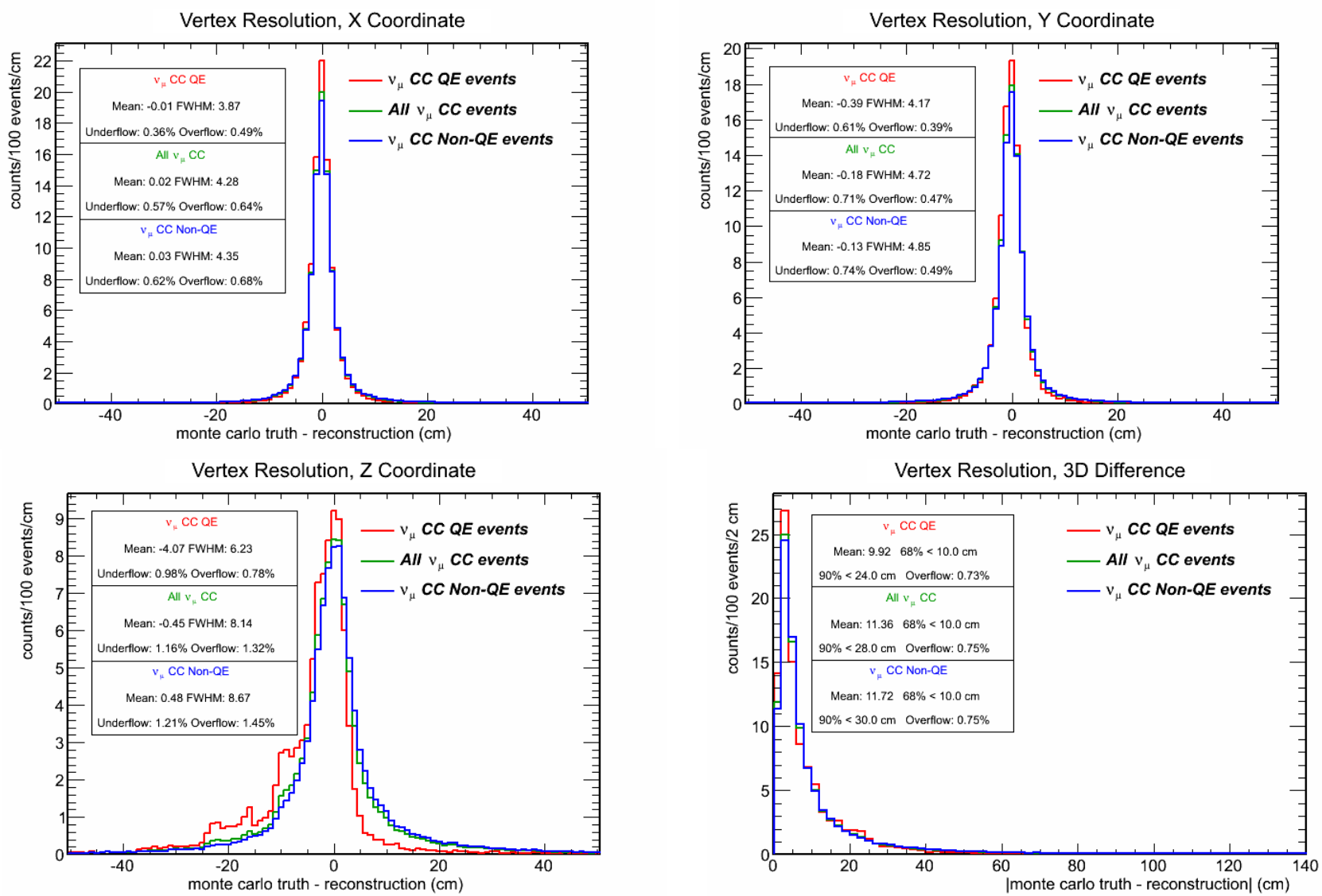

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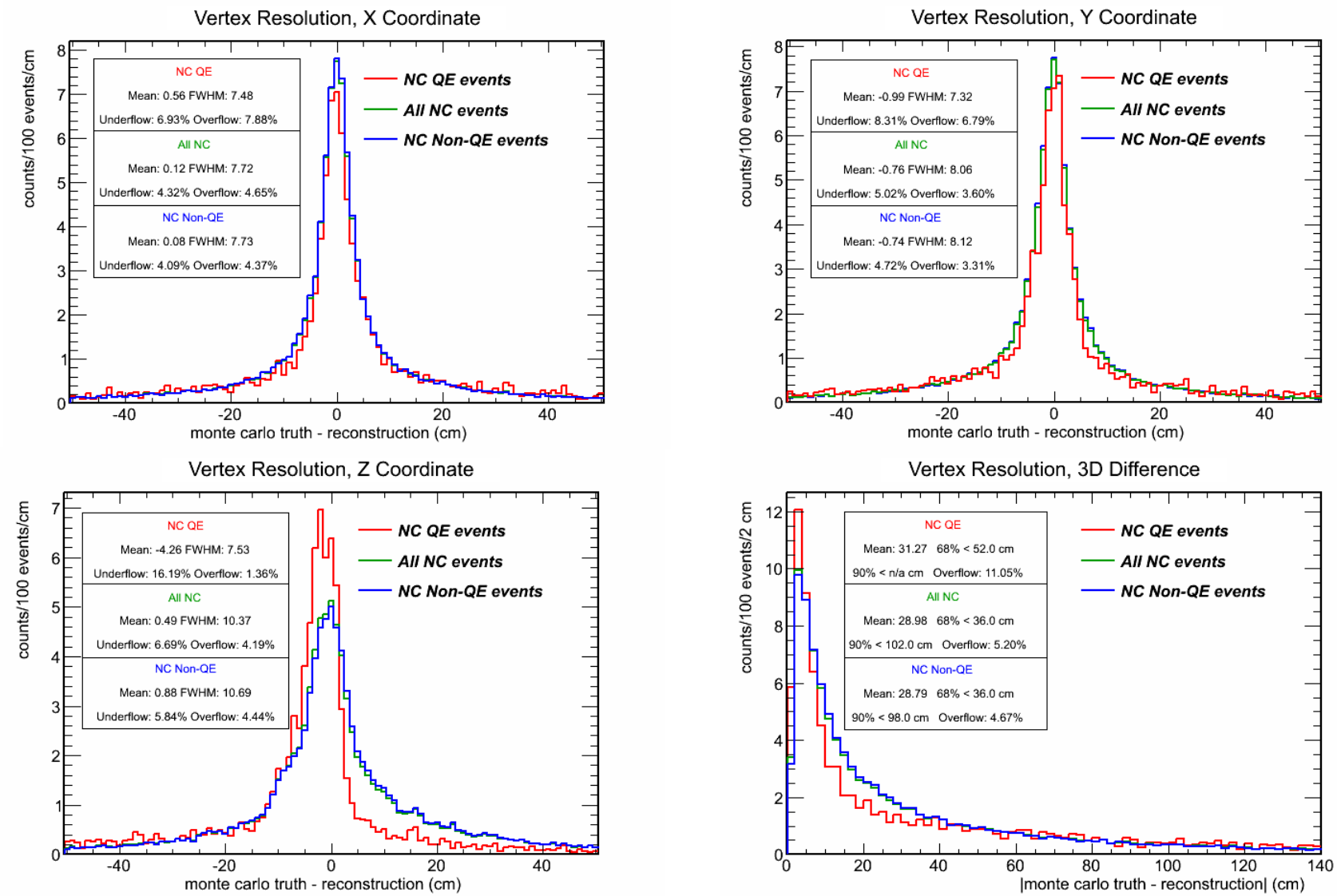
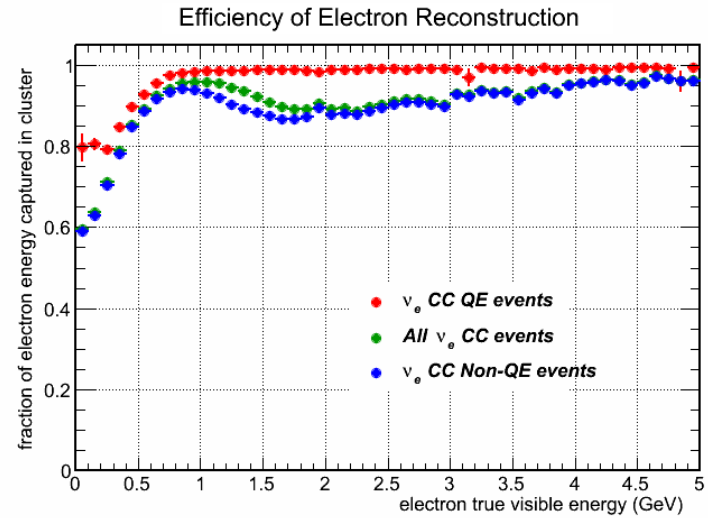
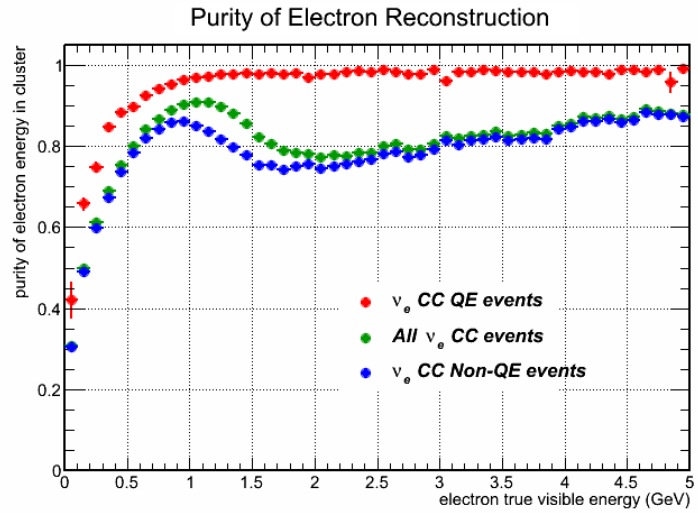
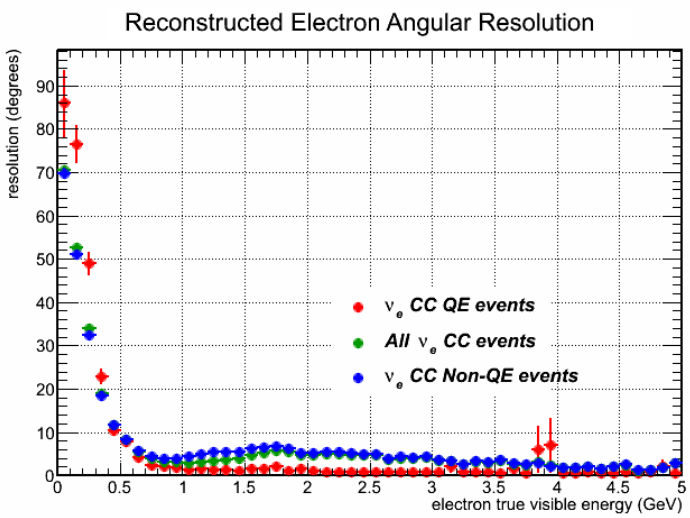
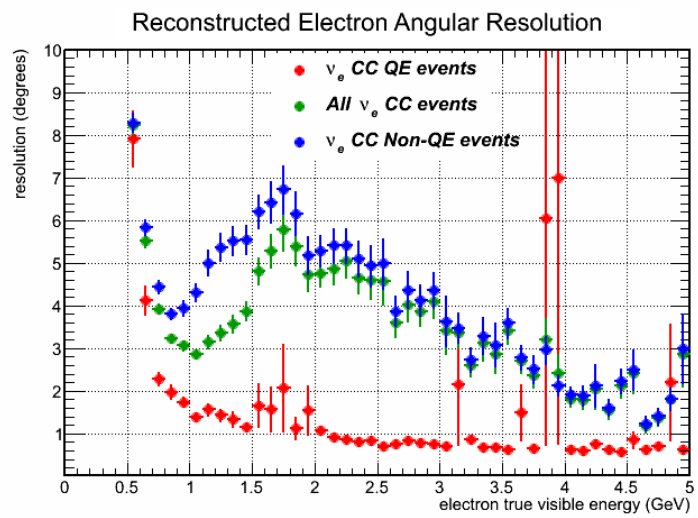


Clustering Performance









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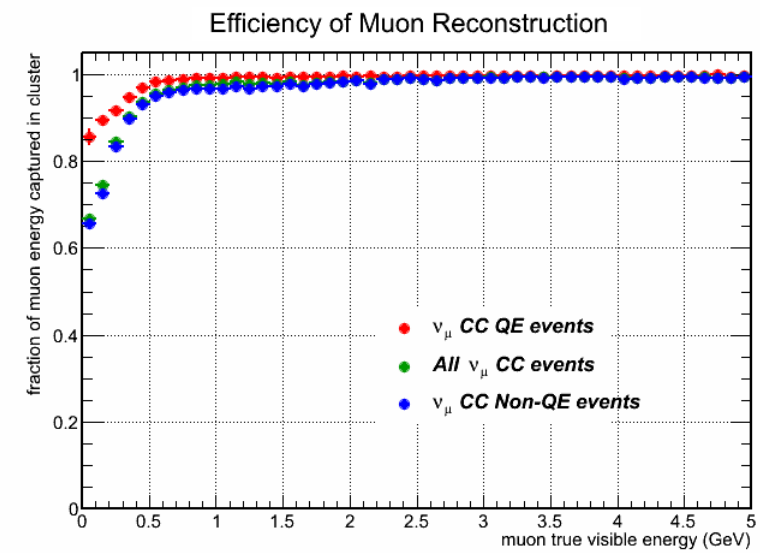
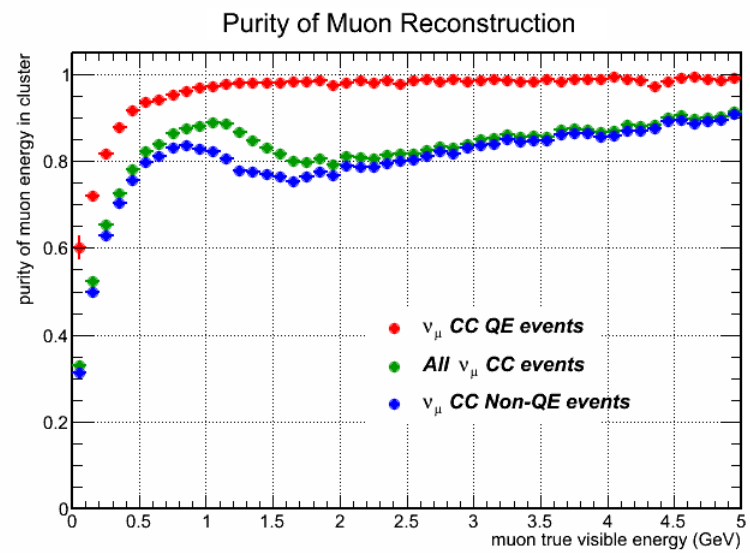
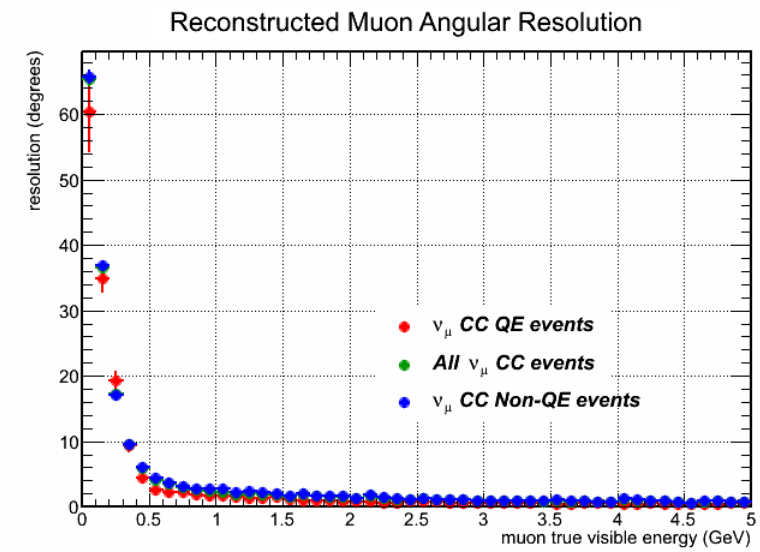
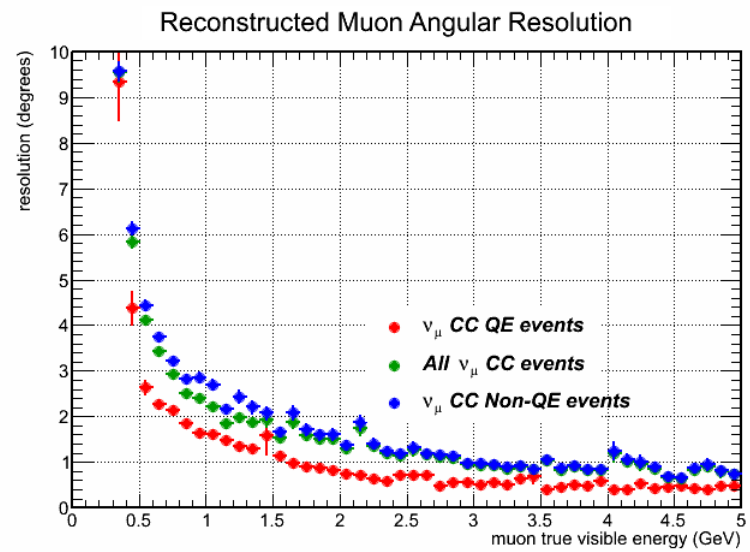
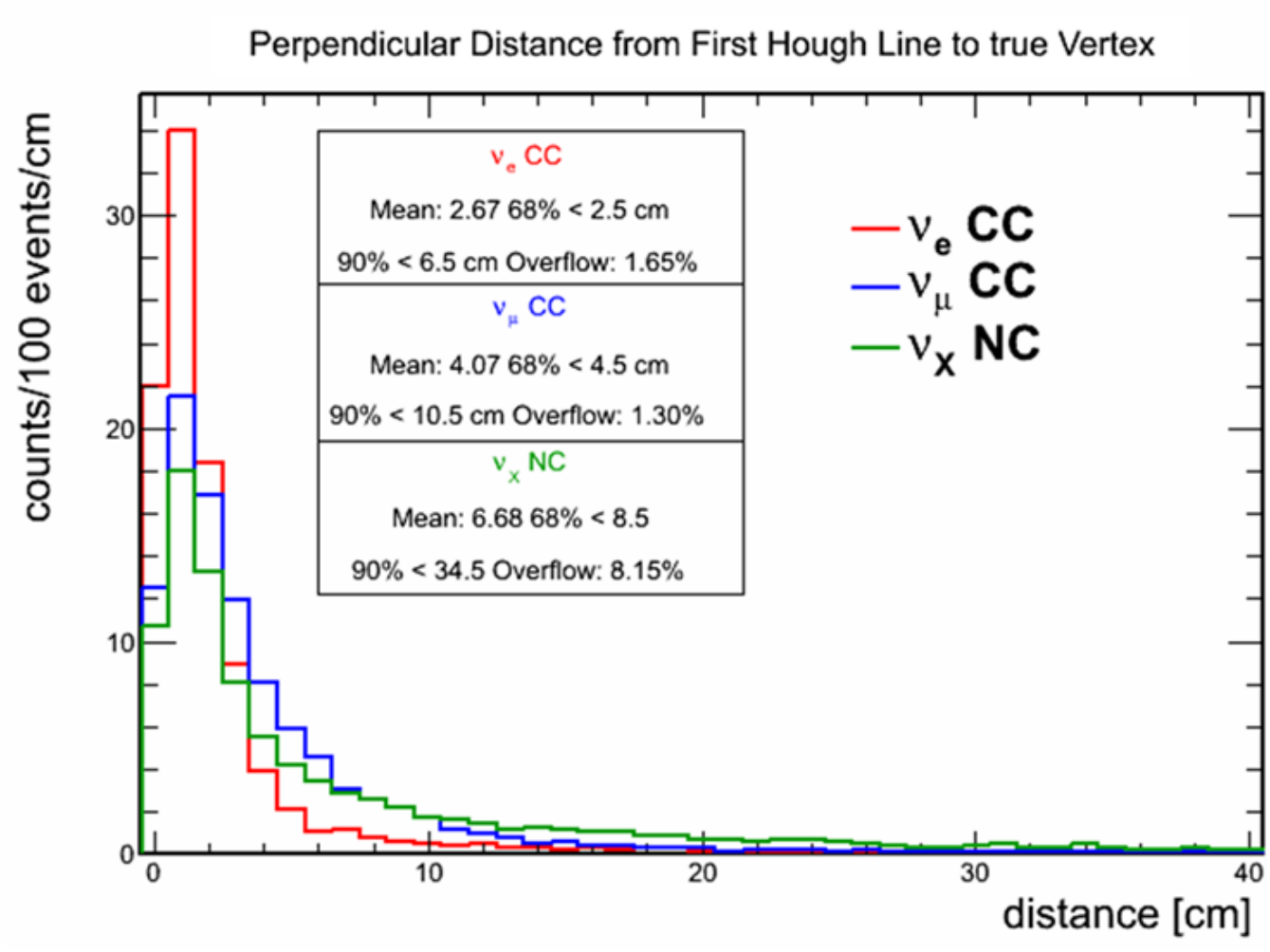


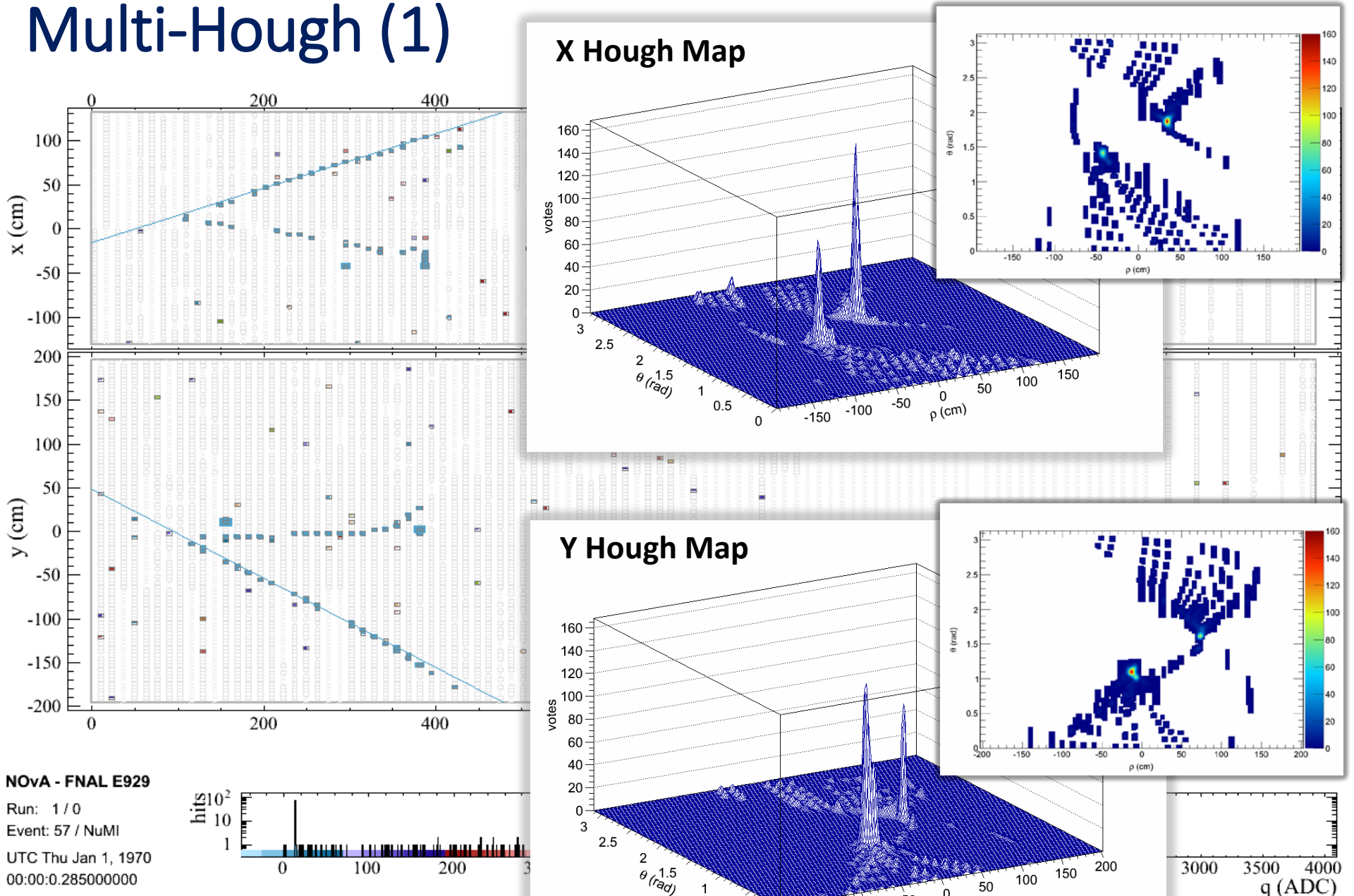




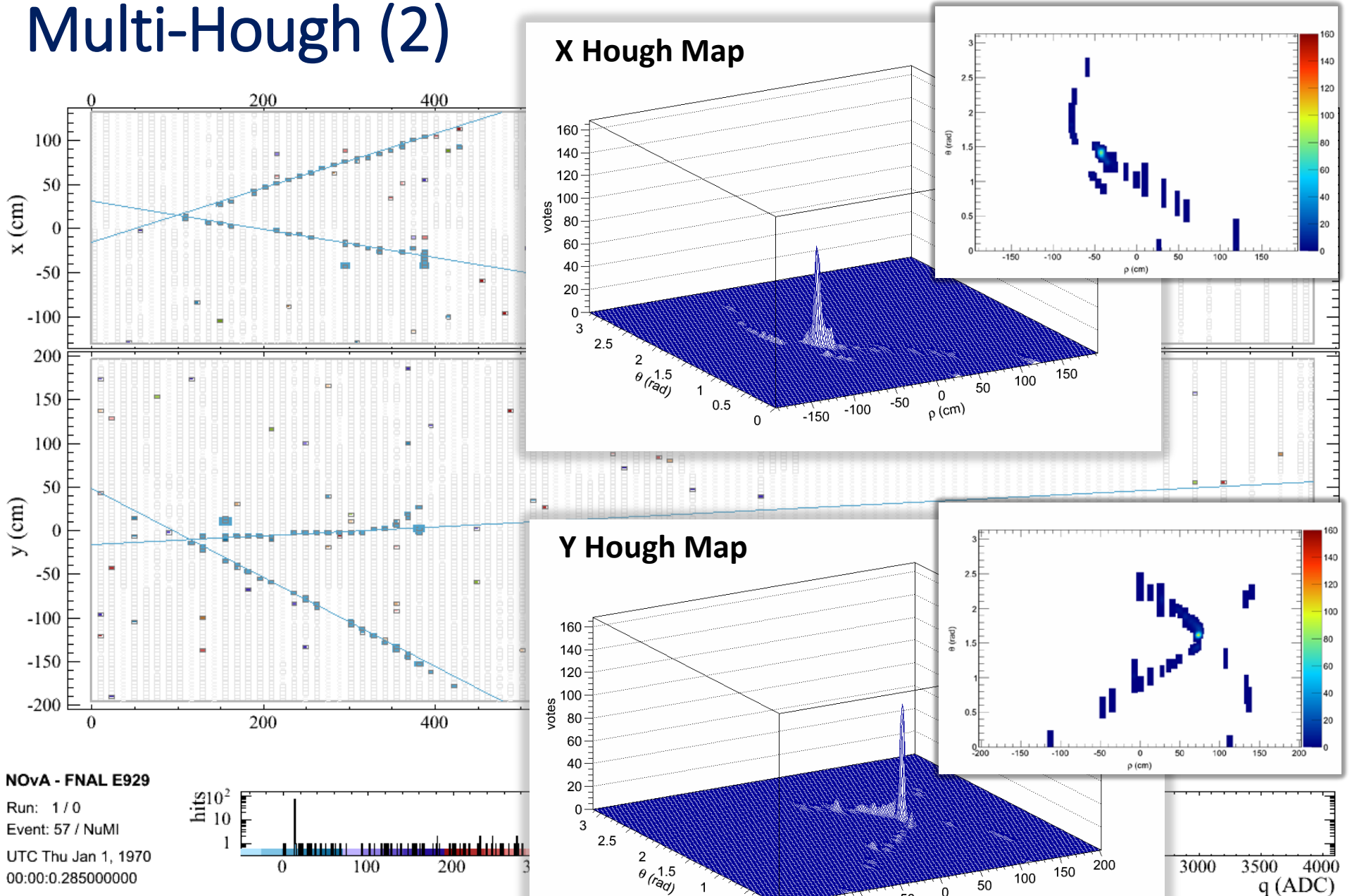



Perpendicular Distance from First Hough Line to true Vertex
counts/100 events/cm
distance [cm]
0
10
20
30
40
ν_e CC
Mean: 2.67 68% < 2.5 cm
90% < 6.5 cm Overflow: 1.65%
ν_μ CC
Mean: 4.07 68% < 4.5 cm
90% < 10.5 cm Overflow: 1.30%
ν_x NC
Mean: 6.68 68% < 8.5
90% < 34.5 Overflow: 8.15%
ν_e CC
ν_μ CC
ν_x NC

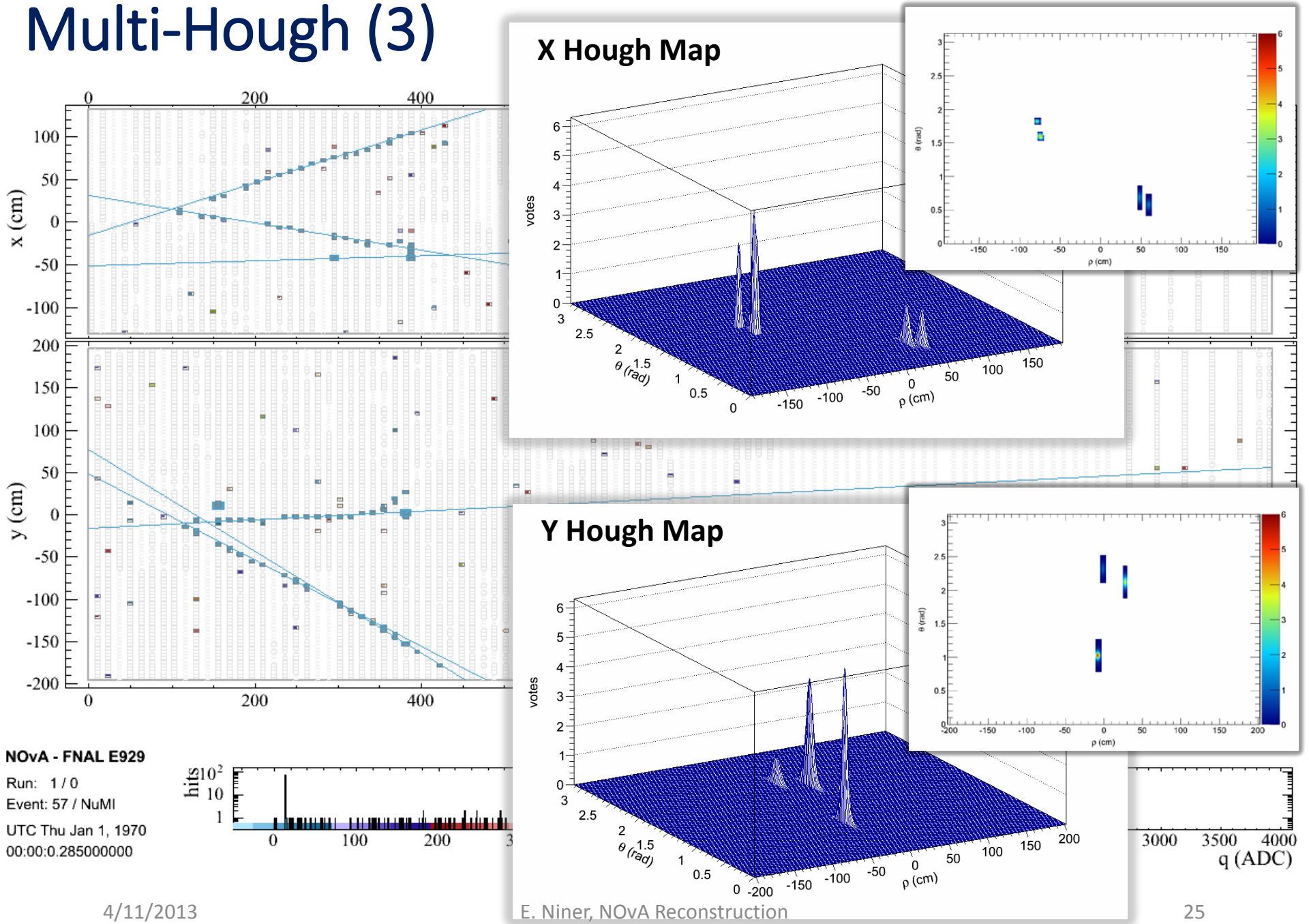
Multi-Hough (1)



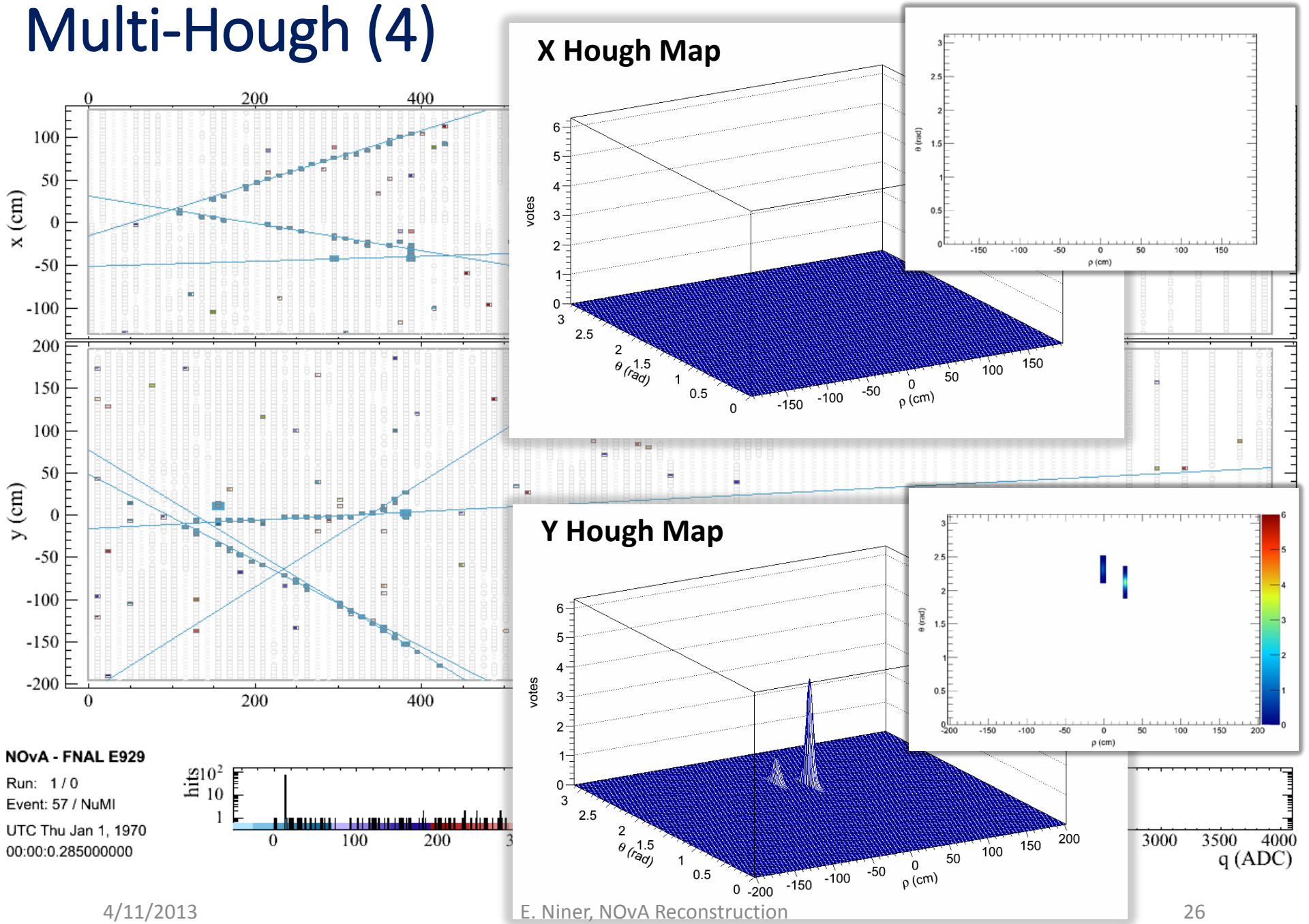
Multi-Hough (2)



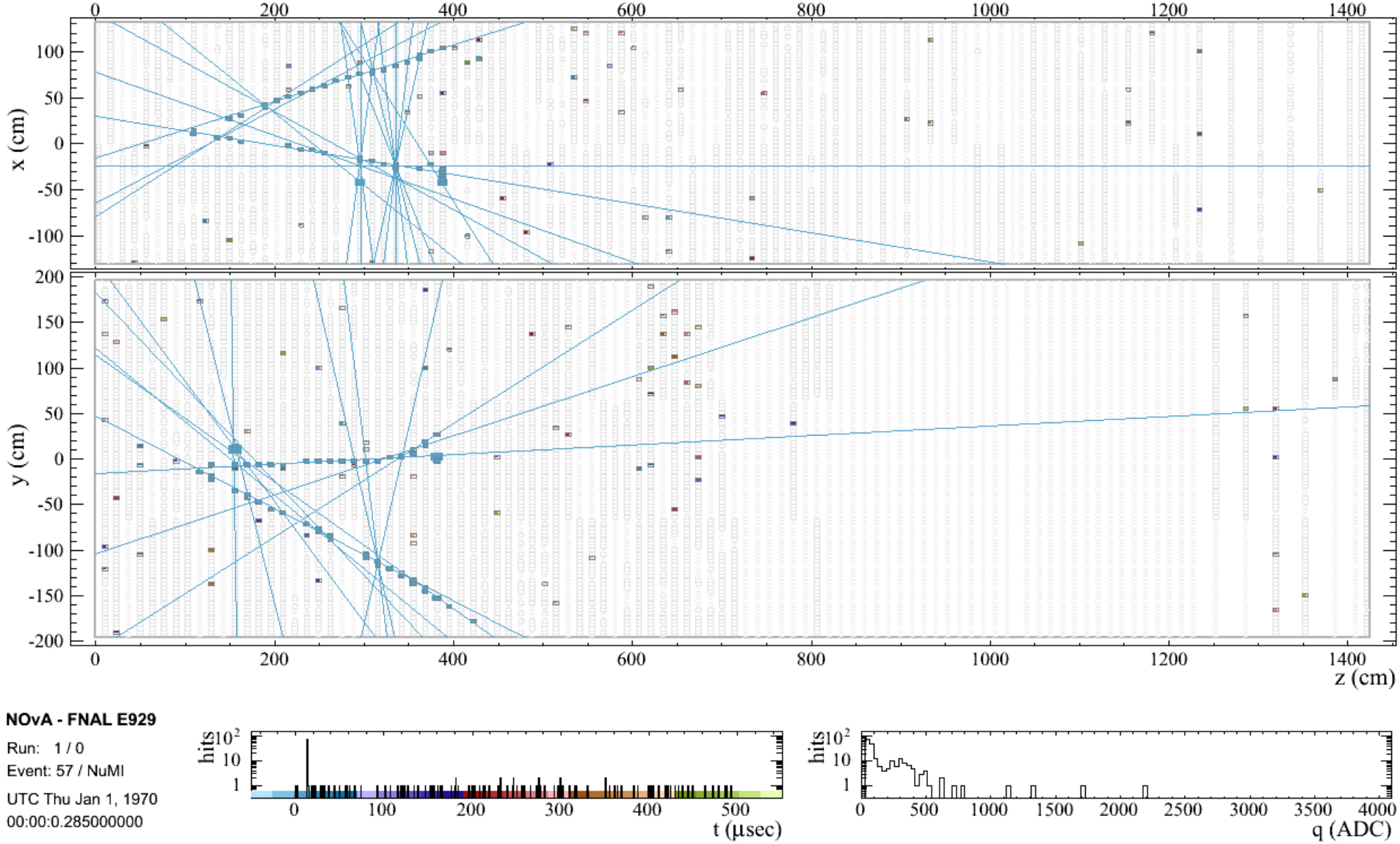
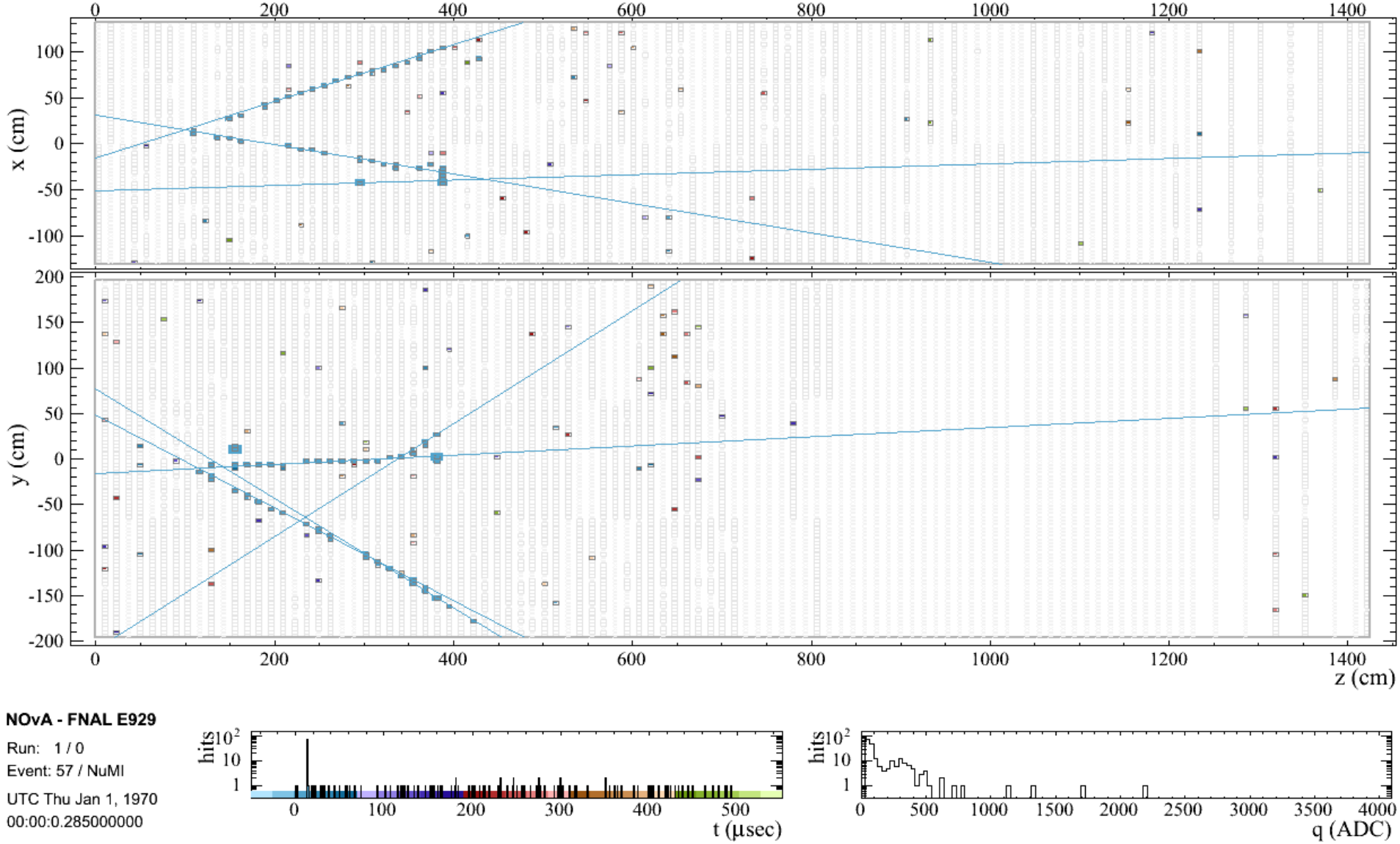
Multi-Hough (3)



Multi-Hough (4)



2 Point Hough transform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