# Summary of the Numu Disappearance Results from the NOvA Experiment



Michael Baird

for the NOvA Collaboration

Monday, 07/31/17

# Neutrino Oscillations:
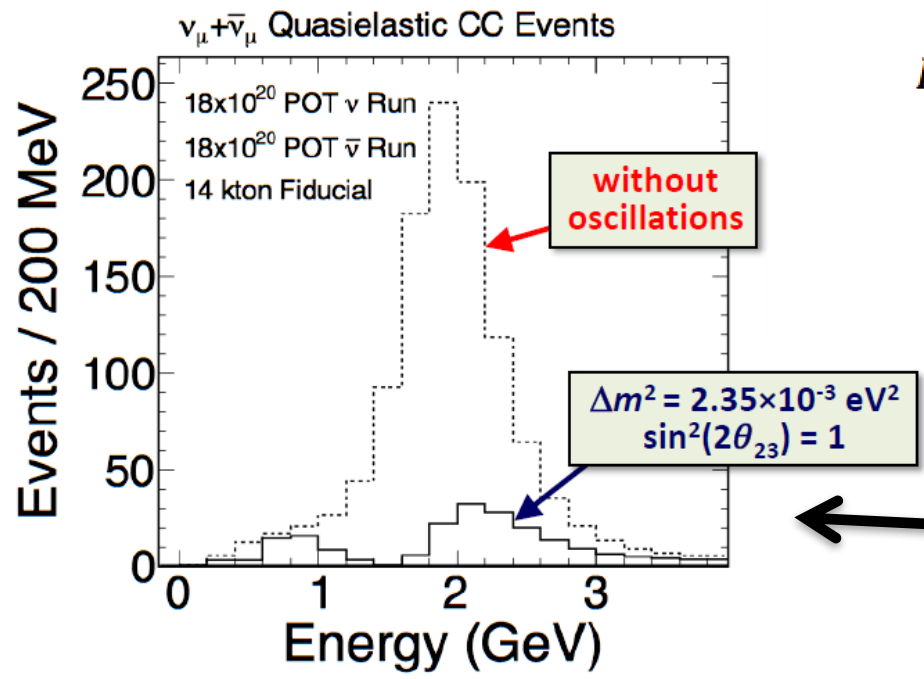
**Neutrino Mixing:**

$$\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{bmatrix} \begin{bmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{bmatrix} \begin{bmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

$$S_{ij} \equiv Sin(\theta_{ij}) \quad C_{ij} \equiv Cos(\theta_{ij})$$

**$v_\mu$ survival probability:**

$$P(v_\mu \rightarrow v_\mu) \approx 1 - sin^2(2\theta_{23})sin^2\left(\frac{1.27\Delta m_{32}{}^2 L}{E}\right)$$

$$\Delta m_{ij}{}^2 \equiv m_i{}^2 - m_j{}^2$$



$v_\mu + \bar{v}_\mu$ Quasielastic CC Events

$18\times10^{20}$ POT $v$ Run
$18\times10^{20}$ POT $\bar{v}$ Run
14 kton Fiducial

**without oscillations**

$\Delta m^2 = 2.35\times10^{-3}$ eV$^2$
$sin^2(2\theta_{23}) = 1$

**(expected NOvA Far Detector $v_\mu$ CC spectra)**

# Neutrino Oscillations:

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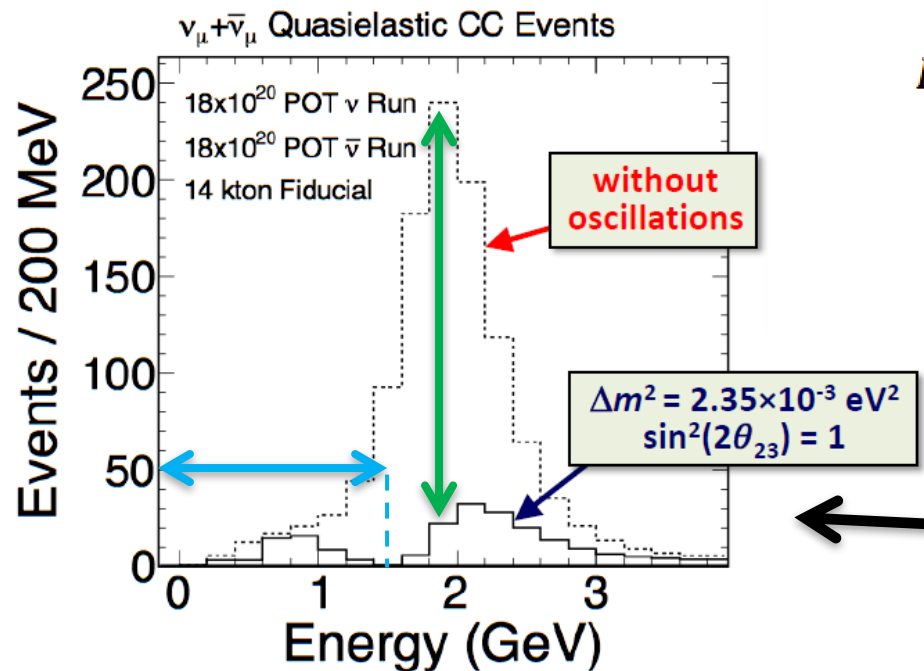$$\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{bmatrix} \begin{bmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{bmatrix} \begin{bmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

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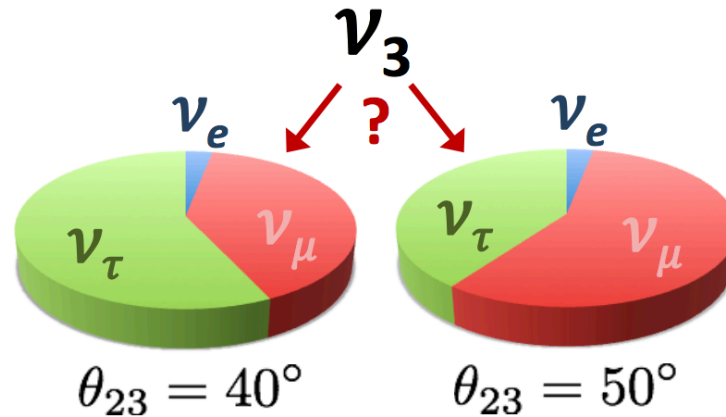$$P(v_\mu \rightarrow v_\mu) \approx 1 - sin^2(2\theta_{23}) sin^2 \left( \frac{1.27\Delta m_{32}^2 L}{E} \right)$$
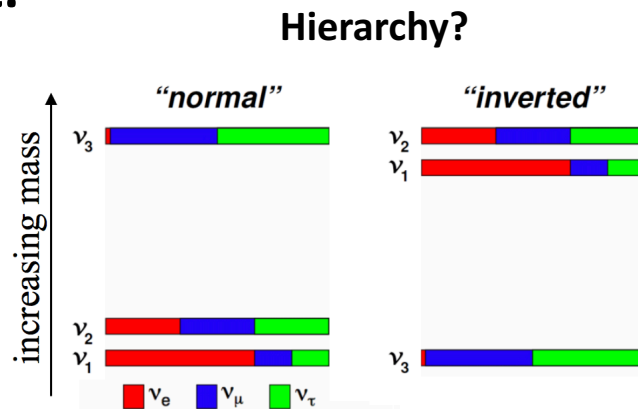
$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$



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**without oscillations**

$\Delta m^2 = 2.35 \times 10^{-3}$ eV$^2$
$sin^2(2\theta_{23}) = 1$

**(expected NOvA Far Detector $v_\mu$ CC spectra)**

# Motivation for a Numu Disappearance Measurement:

1. **A precision measurement of $\theta_{23}$ can help determine the correct texture for the PMNS matrix.**

$$\nu_3$$

$\nu_e$    ?    $\nu_e$

$\nu_\tau$    $\nu_\mu$      $\nu_\tau$    $\nu_\mu$

$$\theta_{23} = 40° \qquad \theta_{23} = 50°$$

2. **An accurate measurement of $\theta_{23}$ improves our $\nu_e$ appearance measurement.**

Hierarchy?                  $\delta_{CP}$?

increasing mass

"normal"          "inverted"

$\nu_3$          $\nu_2$
                $\nu_1$

$\nu_2$
$\nu_1$          $\nu_3$

$\nu_e$    $\nu_\mu$    $\nu_\tau$
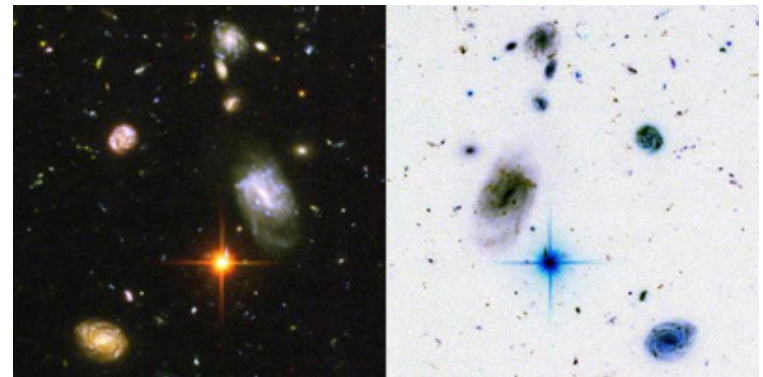
This talk:

- $\nu_\mu$ Disappearance Results – first presented at Nu2016
  **Phys. Rev. Lett. 118, no. 15, 151802 (2017)**

# The NOvA Experiment:  NuMI Beam

**NuMI - <u>Neu</u>trinos at the <u>M</u>ain <u>I</u>njector**

- provides a 10 μsec pulse every 1.33 sec
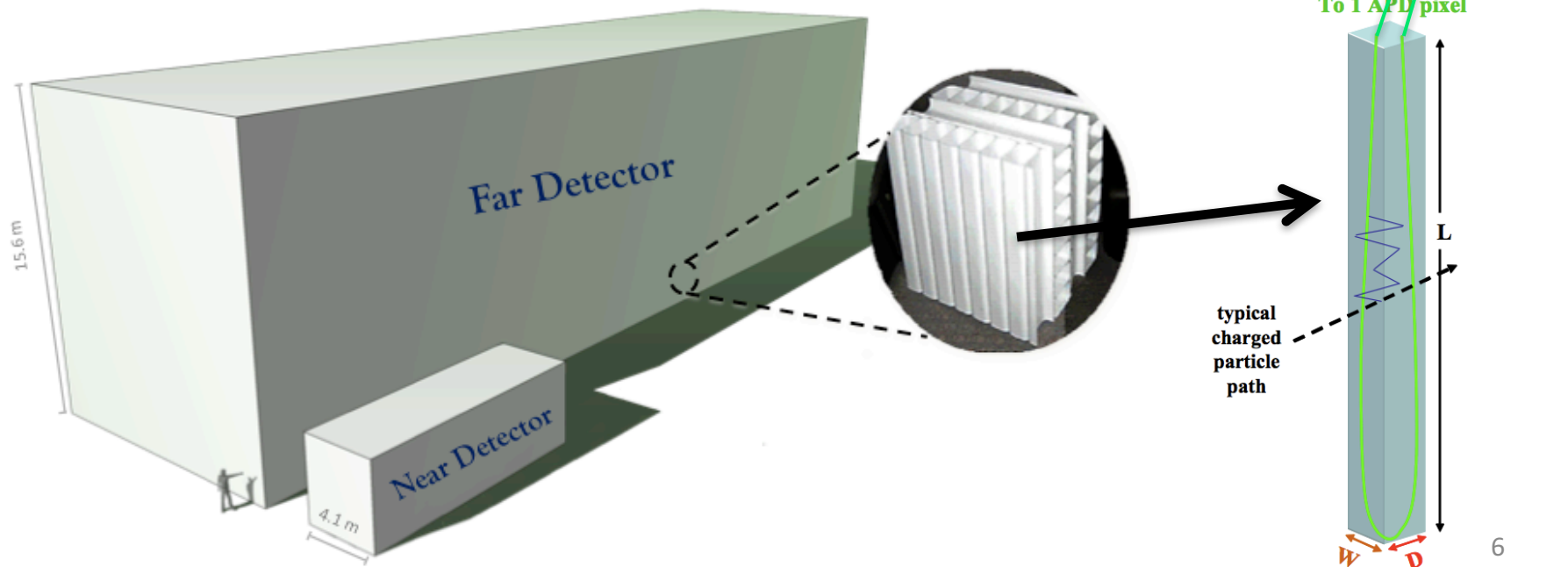
- beam is roughly 98% $\nu_\mu$
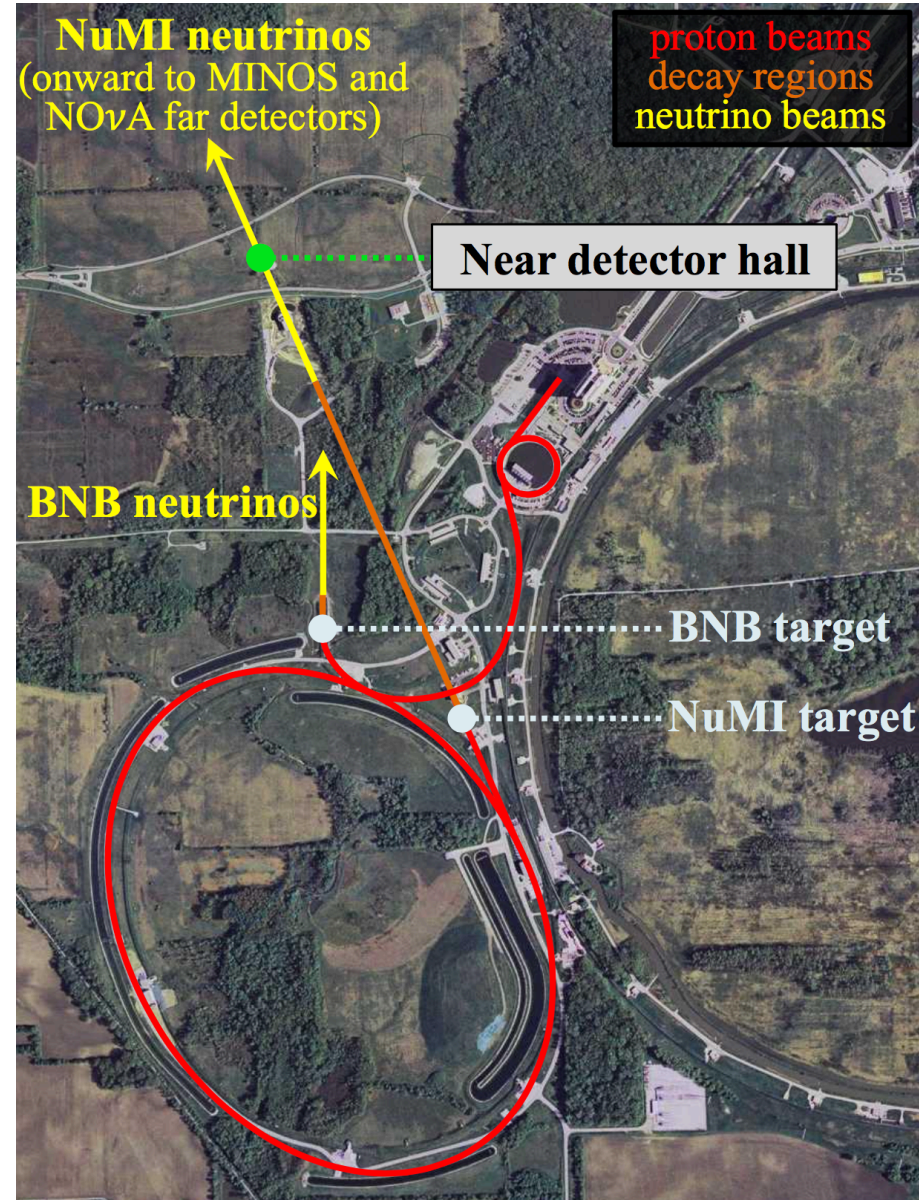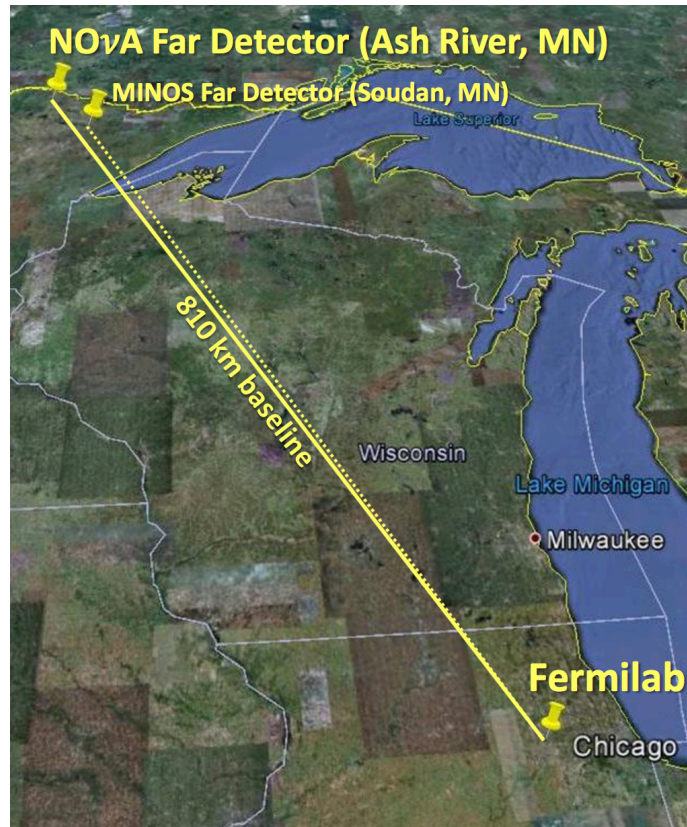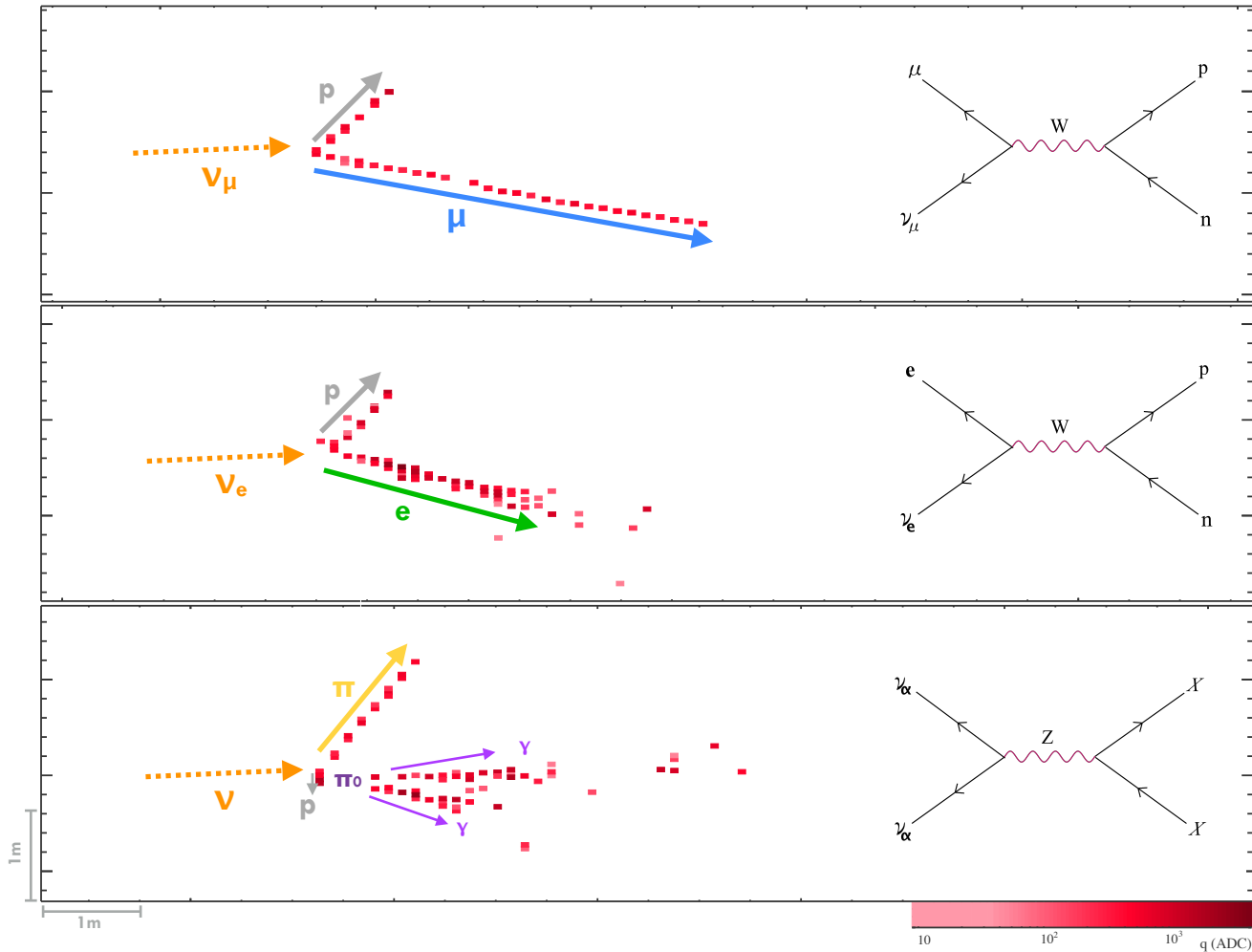
# The NOvA Experiment:   Detectors

**Two functionally identical detectors:**

extruded PVC, mineral oil as scintillator, avalanche photo-diodes for light collection

- **Near:**    300 ton, 1 km from source, 105 m underground
- **Far:**     14 kton, 810 km from source, on the surface

Far Detector

15.6 m

Near Detector

4.1 m

To 1 APD pixel

L

typical charged particle path

W    D

# The NOvA Experiment:  Detectors



- NOvA is a highly active tracking calorimeter.
- The detectors are designed with low-Z materials (mineral oil and PVC) so as to enhance the differences between muon tracks, showers caused by electrons, and showers caused by pi-zeros.
  - Moliere radius = 11 cm
  - EM radiation length = 40 cm
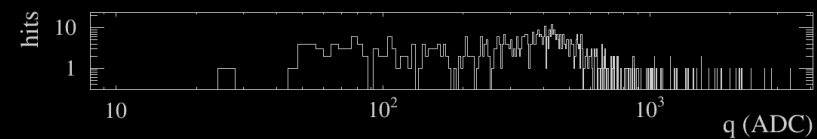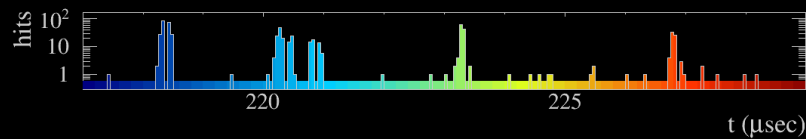
# Near Detector Event Display
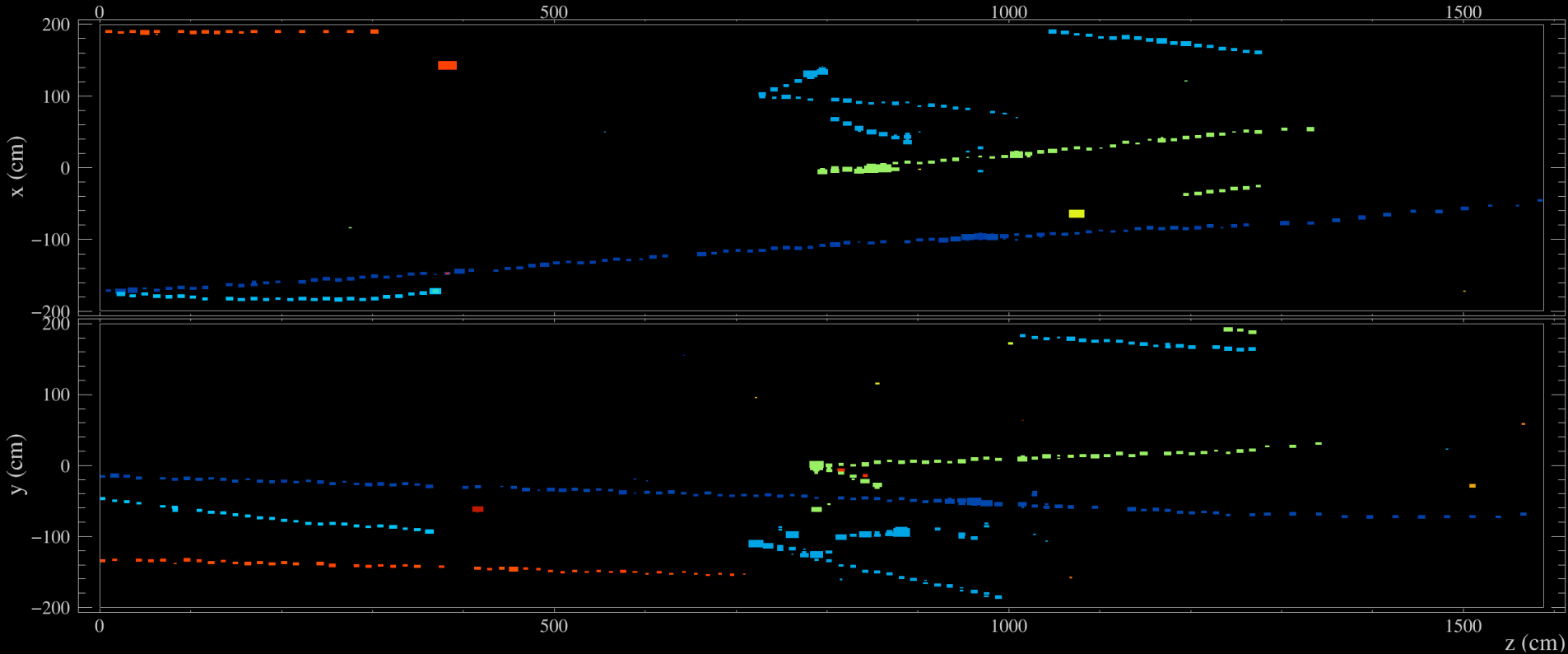


NOvA - FNAL E929
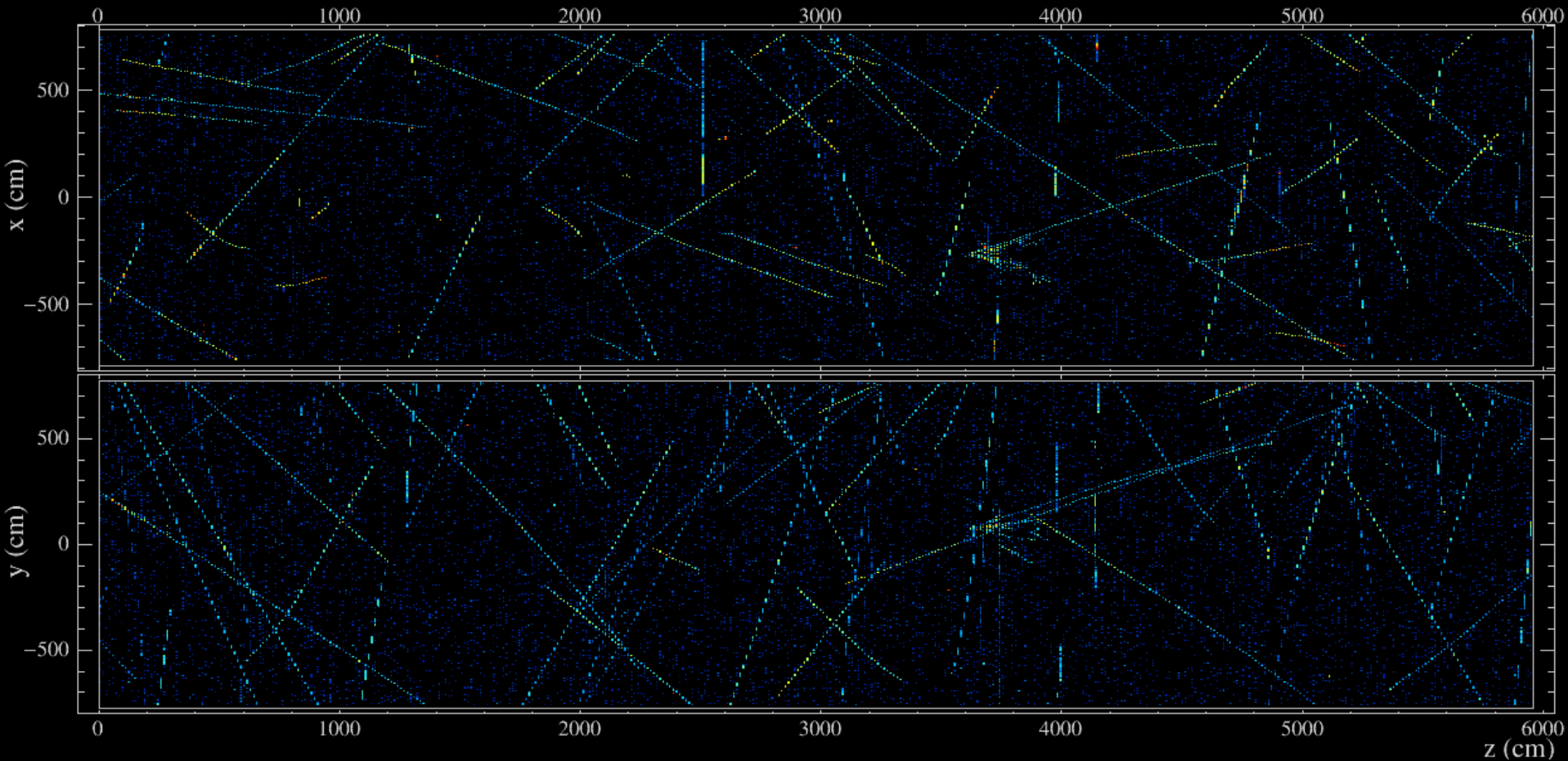
Run: 10407 / 1
Event: 27950 / --
UTC Thu Sep 4, 2014
05:28:44.034495968

(colors show hit times)

# Far Detector Event Display

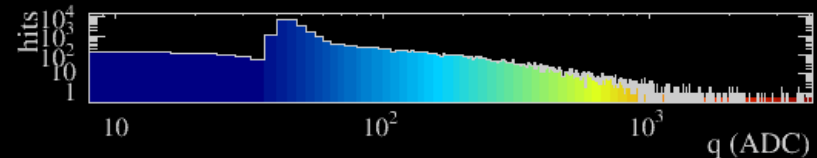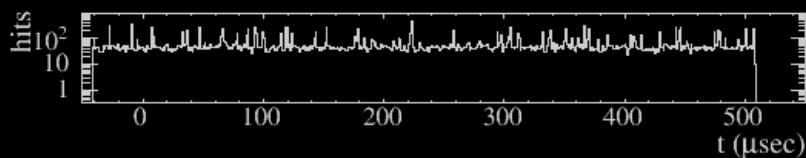

(colors show charge)

# Far Detector Event Display
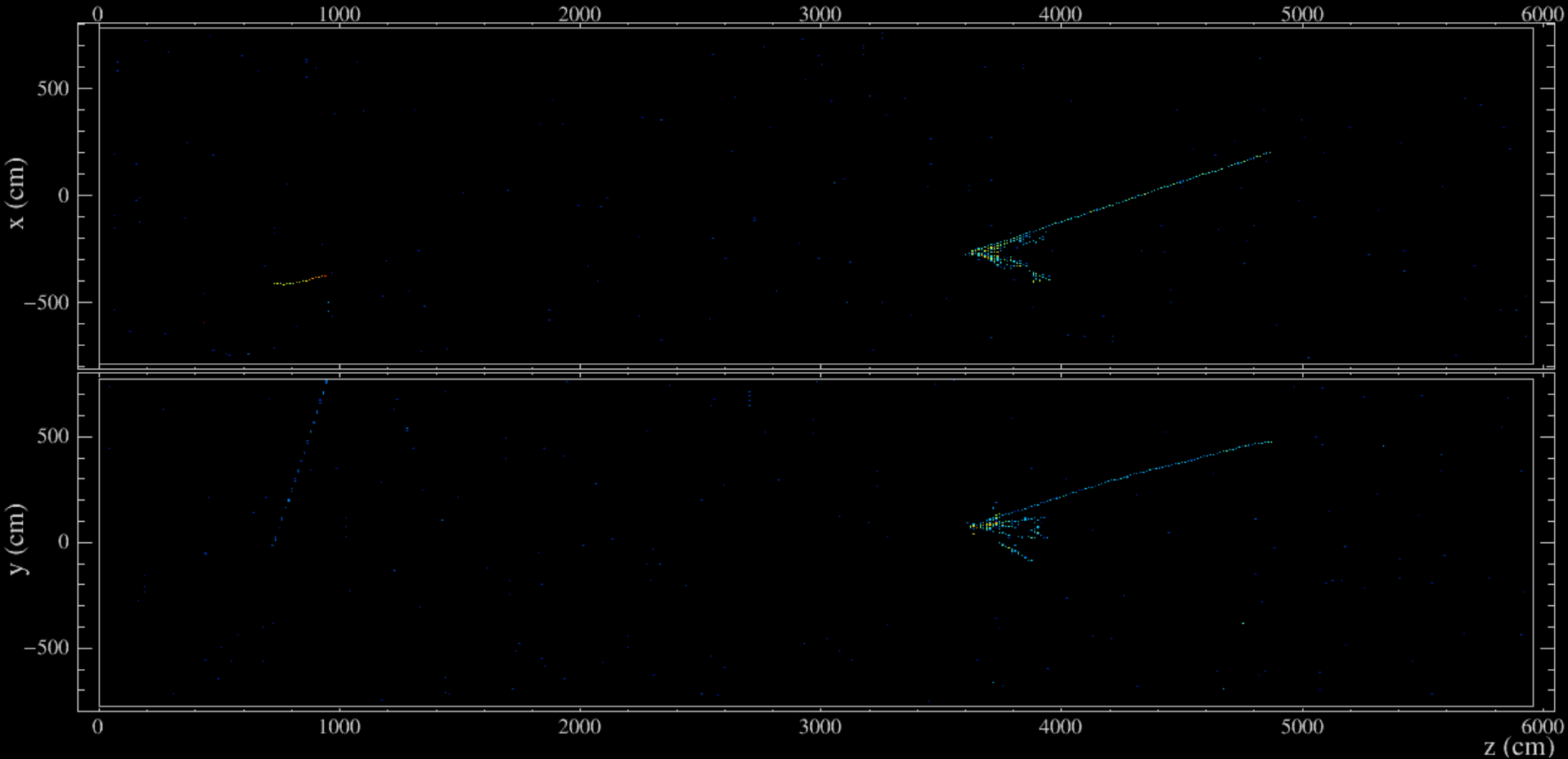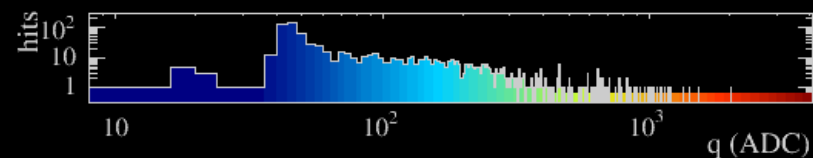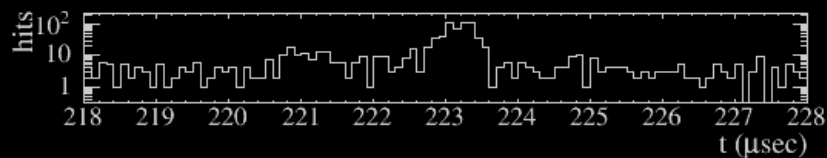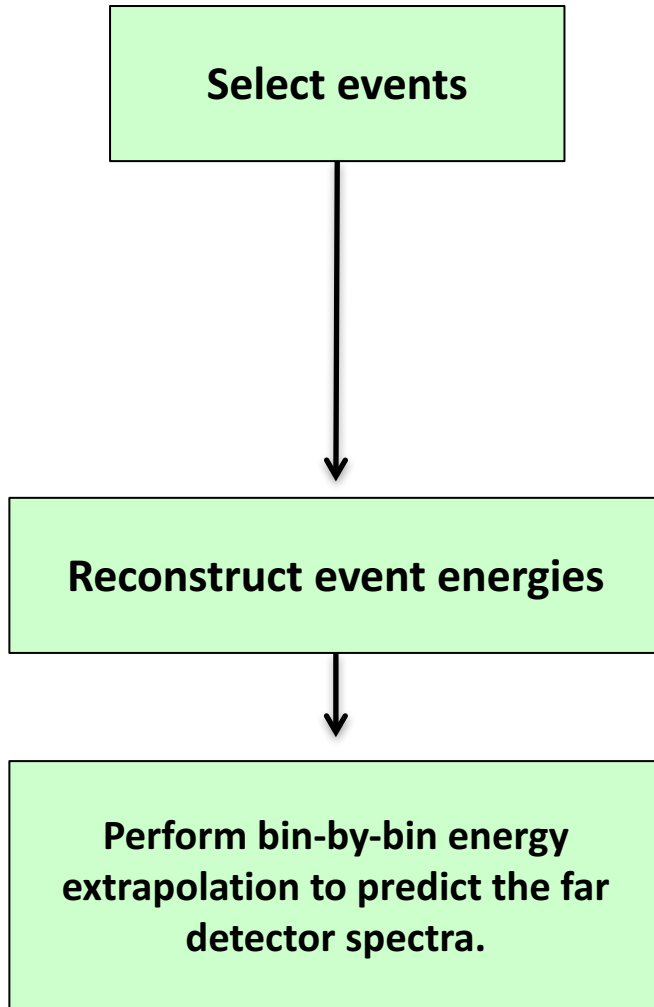


(colors show charge)     zoomed in on beam window

# $\nu_\mu$ Disappearance Analysis Outline:

**Near Detector:**

**Far Detector:**

```
Near Detector:
  Select events
      ↓
  Reconstruct event energies
      ↓
  Perform bin-by-bin energy extrapolation to predict the far detector spectra.  ──→

Far Detector:
  Select events
      ↓
  Reject cosmics
      ↓
  Reconstruct event energies
      ↓
  Use extrapolated spectra to fit for the oscillation parameters.
```
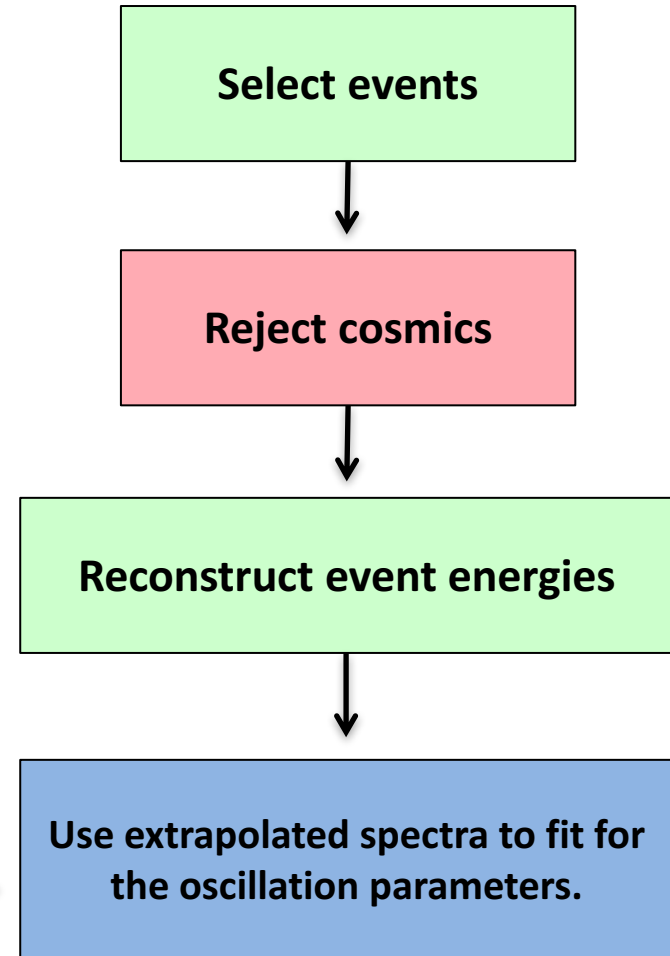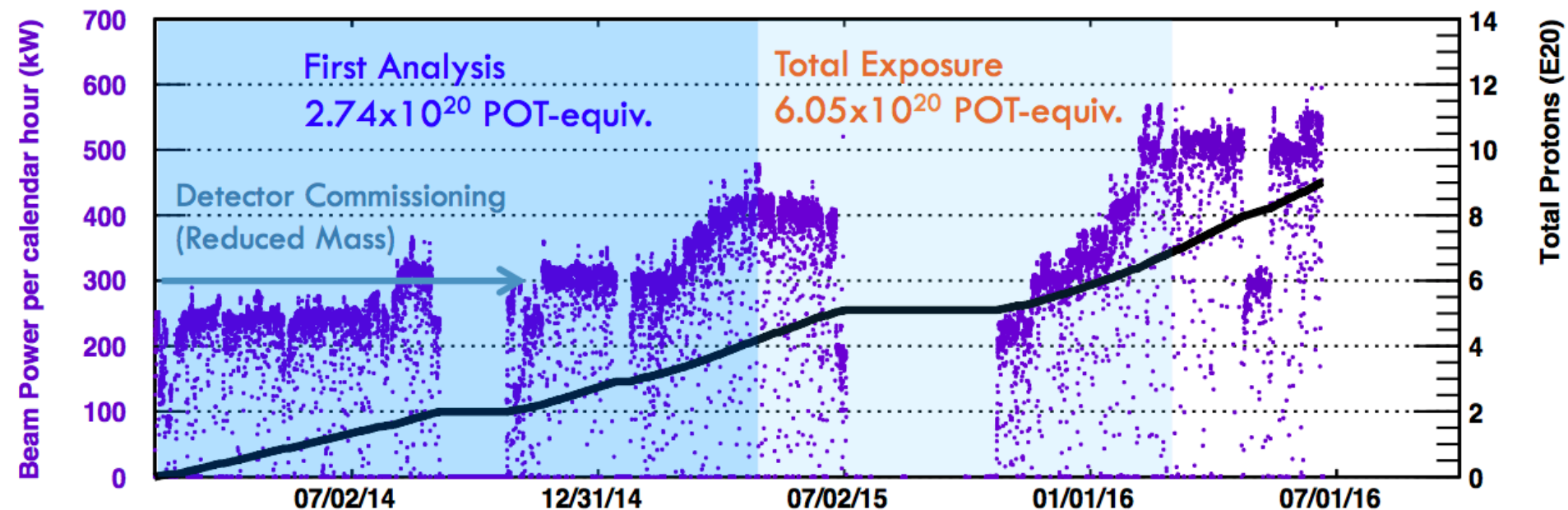
# NOvA Data Collection:

- Feb 6th 2014 – May 2nd 2016, equivalent to 6.05 x 10$^{20}$ POT (in a full 14 kT detector.)
- See Diana Mendez's talk (next) for improvements in the next analysis with data taken since May 2nd 2016.

- **The NuMI beam has now reached the 700 kW design goal, making it the most powerful neutrino beam in the world!**

# NOvA Simulation Tuning:

- Analysis of the NOvA ND data suggested an additional event rate and alteration of the kinematic distributions arising in neutrino scattering on nuclei.

- DIS events with W < 1.7 GeV were weighted down by 35%.

- We enabled an empirical Meson Exchange Current (MEC) model within GENIE, and reweighted those events as a function of 3-momentum transfer.
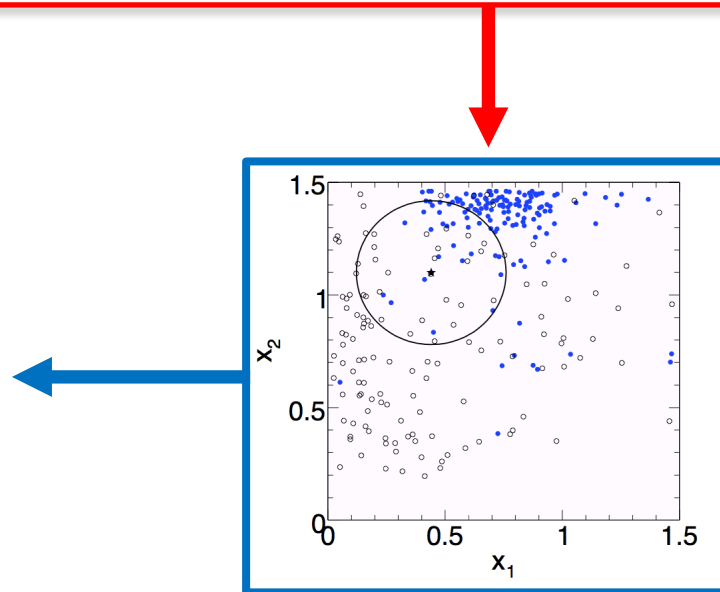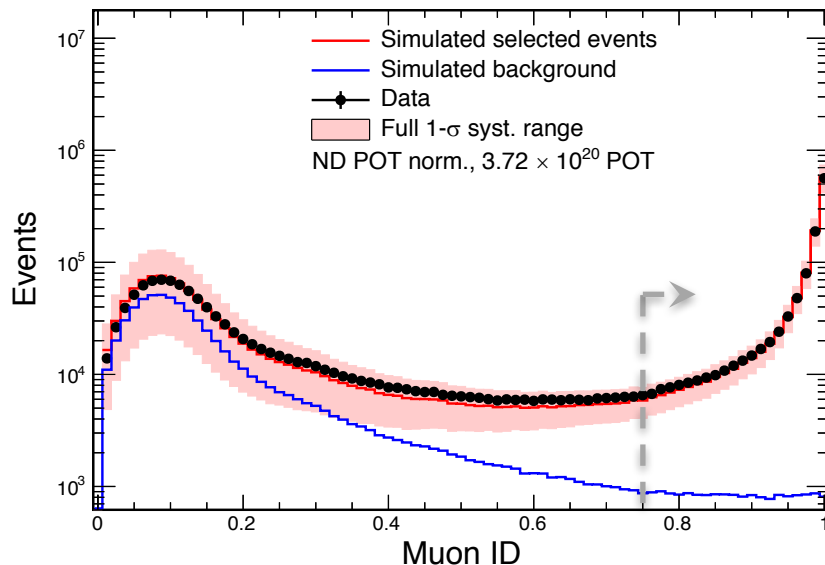


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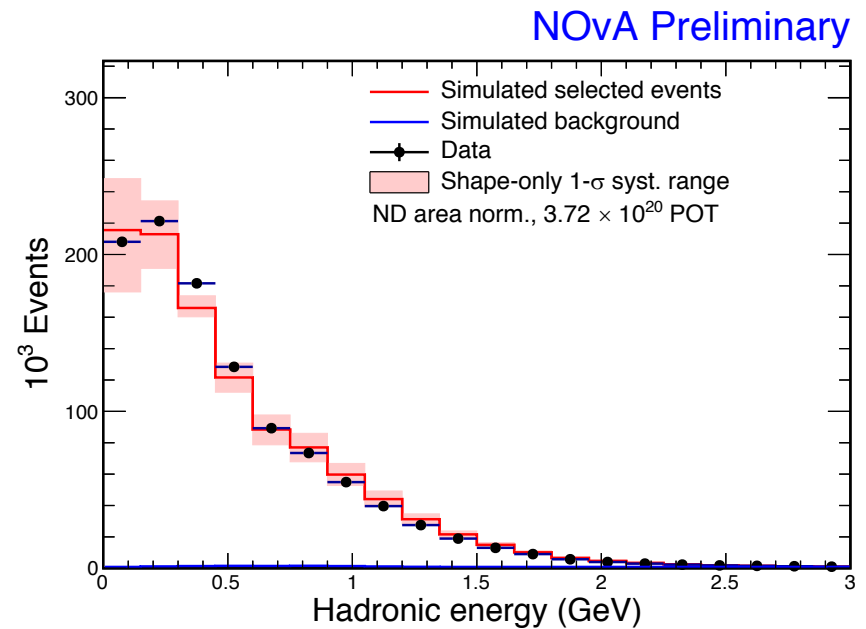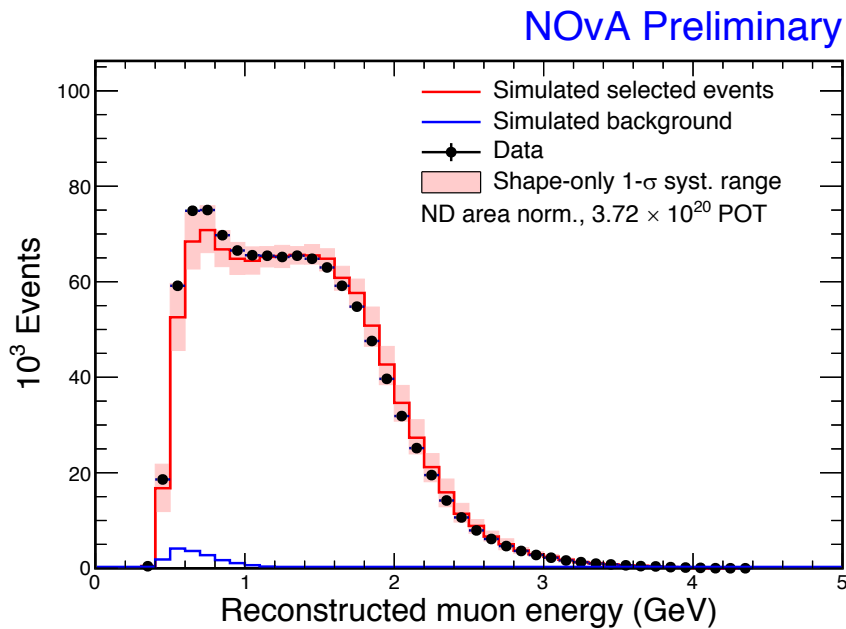
# Event Selection:

- Choose $\nu_\mu$ CC events with a traditional kNN.

- Using 4 reconstructed track variables as input.

- See talk by F.Psihas Wed. 08/02 11:10 am on advancements in event selection.



NOvA Preliminary





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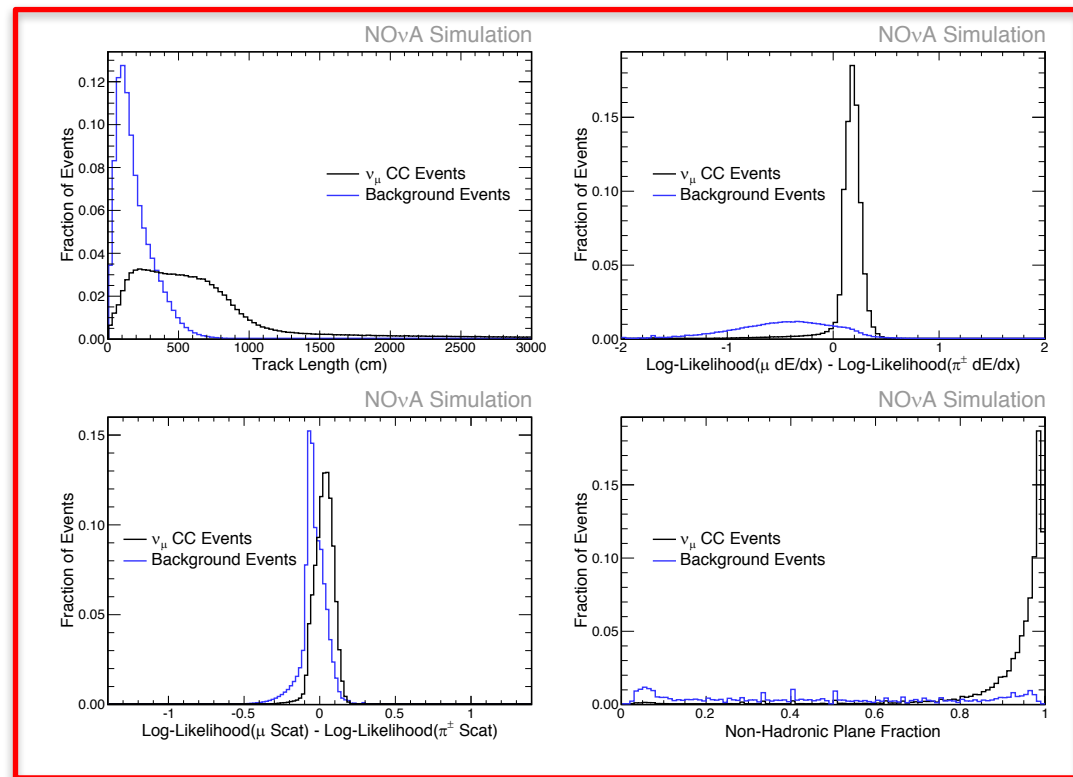
# Far Detector Cosmic Rejection:

- We expect ~65,000 cosmic rays in-time with the NuMI beam spills per day. The expected number of contained $\nu_\mu$ CC events per day is only a few.

- Containment cuts will remove 99% of the cosmics.

- We use a boosted-decision-tree (BDT) algorithm that takes input from reconstruction variables to reject the remaining cosmics.
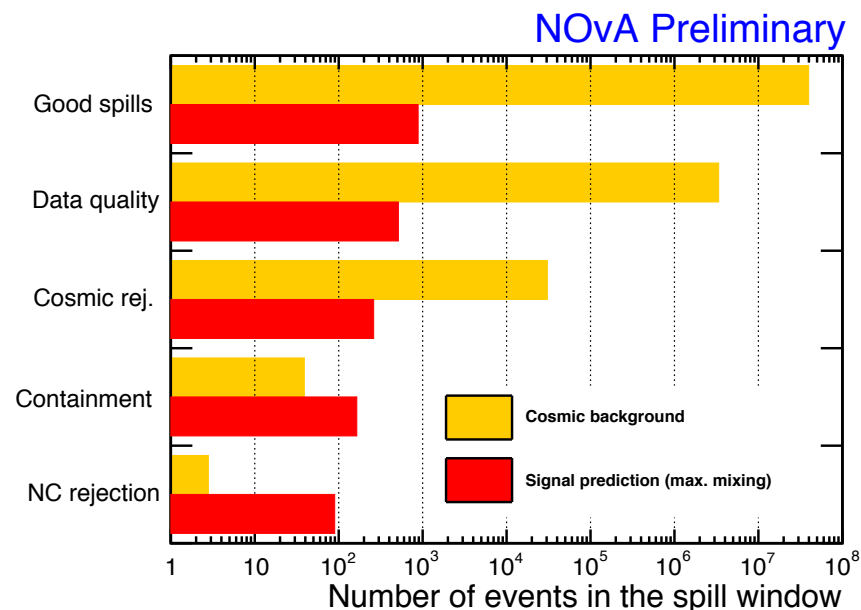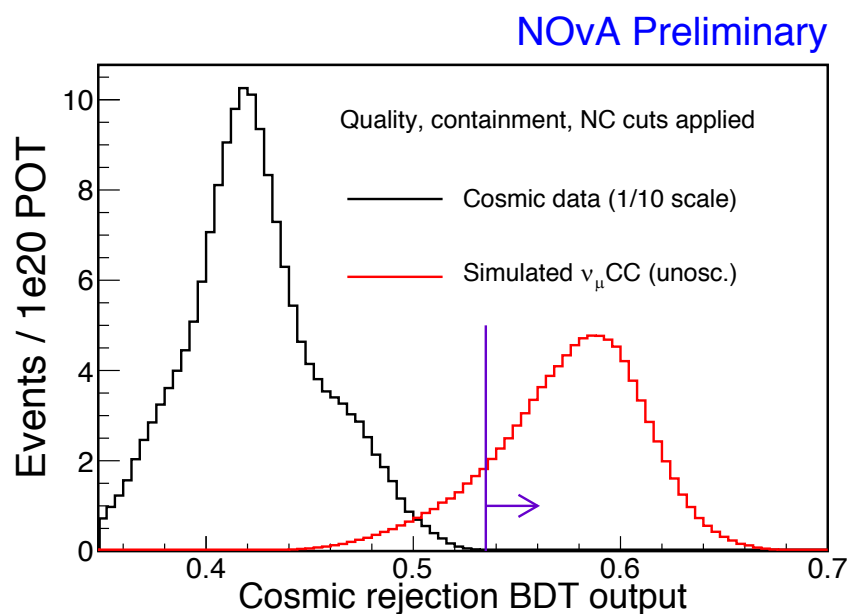


**All cuts together give us > 15:1 s:b.**

**Cosmics are reduced by $10^7$!**

# Energy Estimation:

**Reconstructed muon track:**
length $\Rightarrow E_\mu$

**Hadronic system:**
$$\sum_{\text{cells}} E_{\text{visible}} \Rightarrow E_{\text{had}}$$

**Reconstructed $\nu_\mu$ energy is the sum of these two:**
$$E_\nu = E_\mu + E_{\text{had}}$$

*Energy resolution at beam peak ~7%*

# Far Detector Prediction:

**The far detector prediction is generated using a near to far extrapolation process.**

ND reconstructed E spectra



- ND Data
- Base Simulation
- Data-Driven Prediction

$2.74 \times 10^{20}$ FD POT-equiv.
$1.66 \times 10^{20}$ ND POT

# Far Detector Prediction:

**The far detector prediction is generated using a near to far extrapolation process.**

ND reconstructed E spectra



| | |
|---|---|
| — ND Data | $2.74 \times 10^{20}$ FD POT-equiv. |
| — Base Simulation | $1.66 \times 10^{20}$ ND POT |
| — Data-Driven Prediction | |

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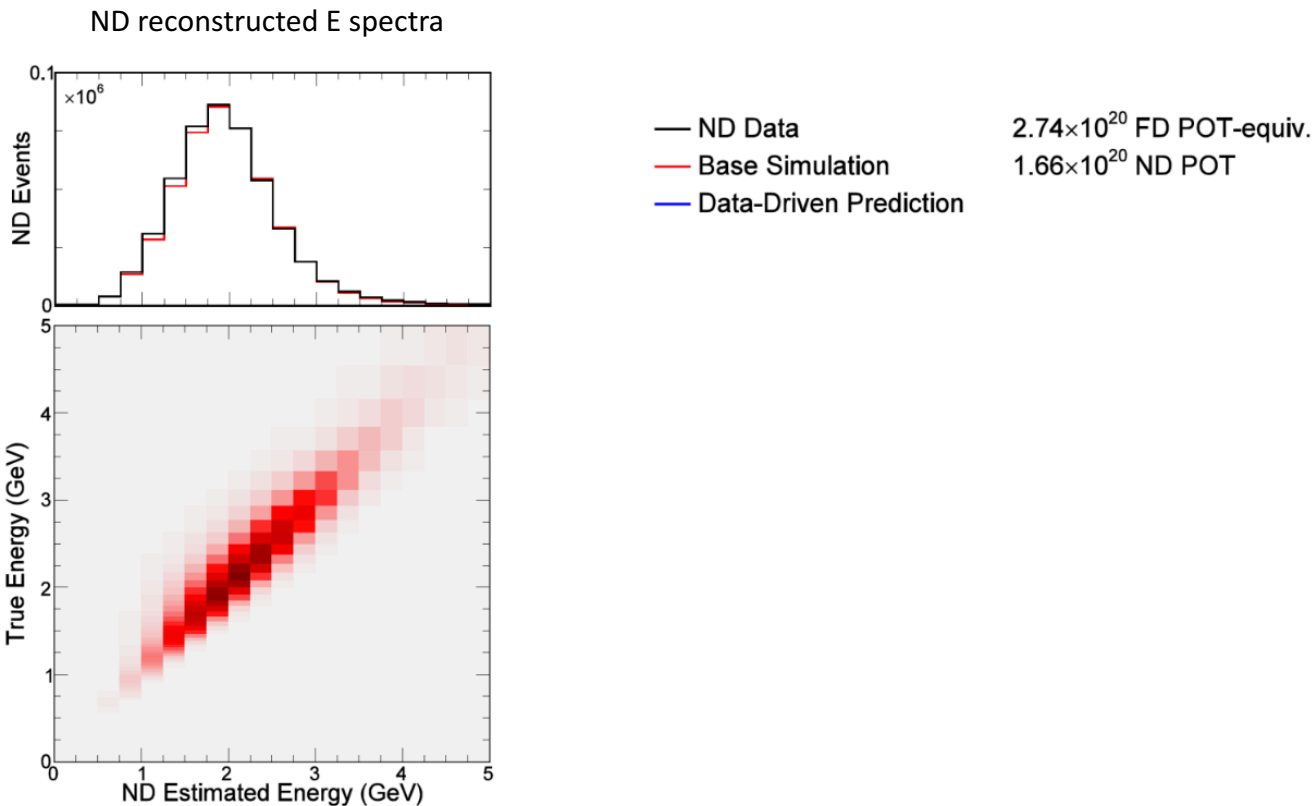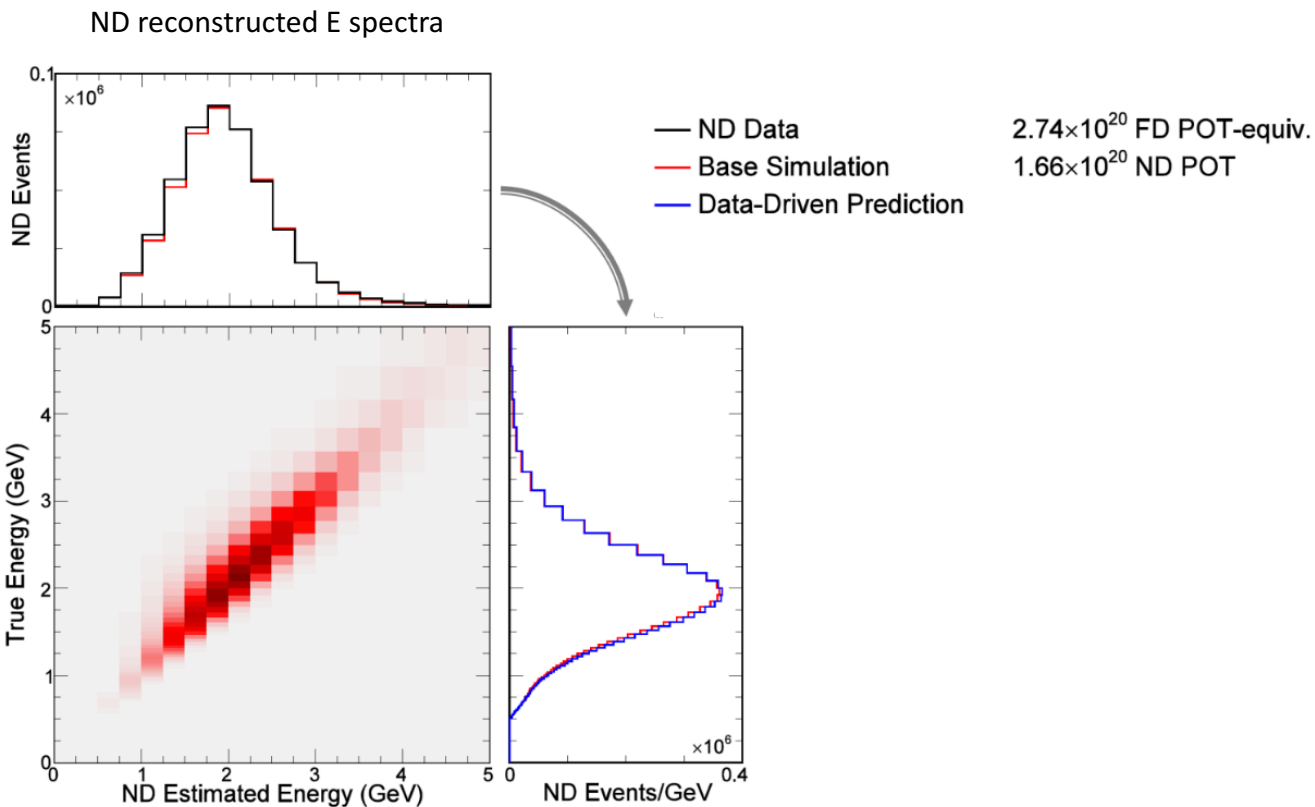# Far Detector Prediction:

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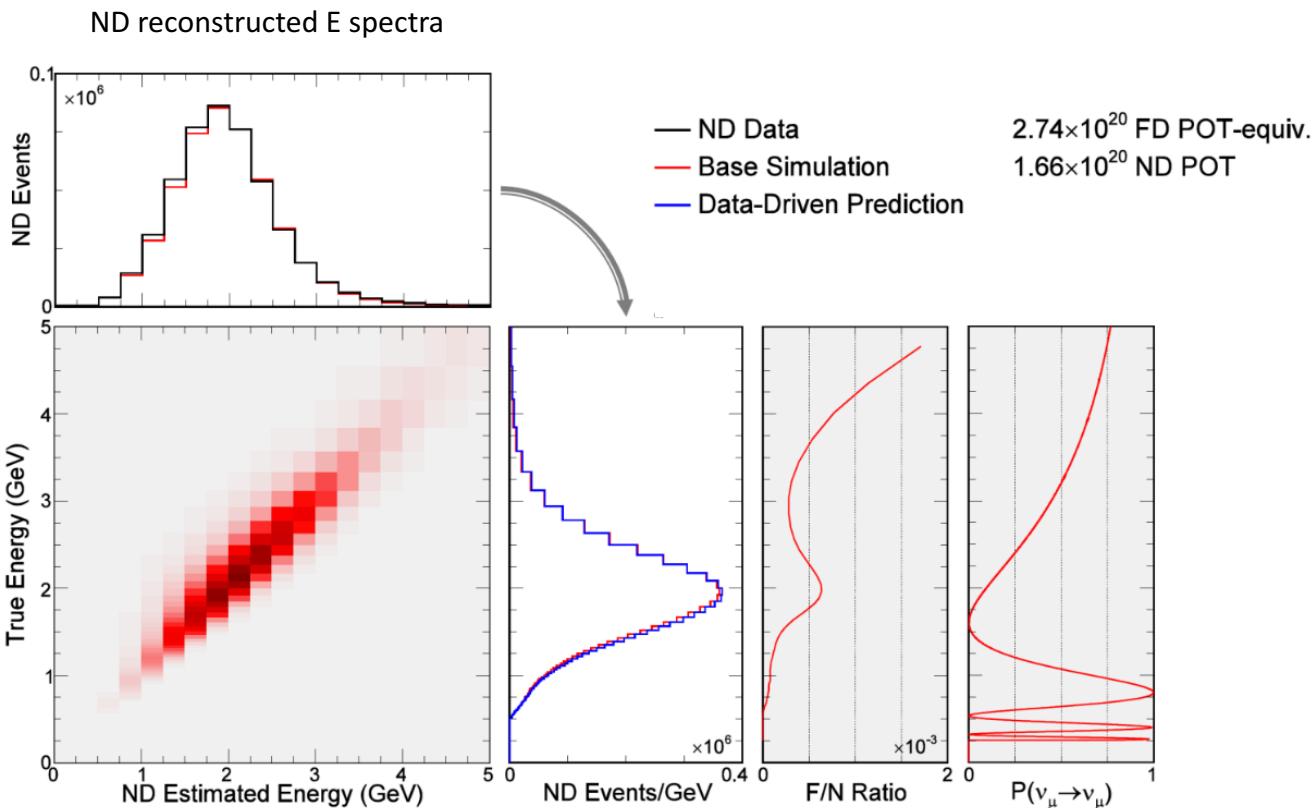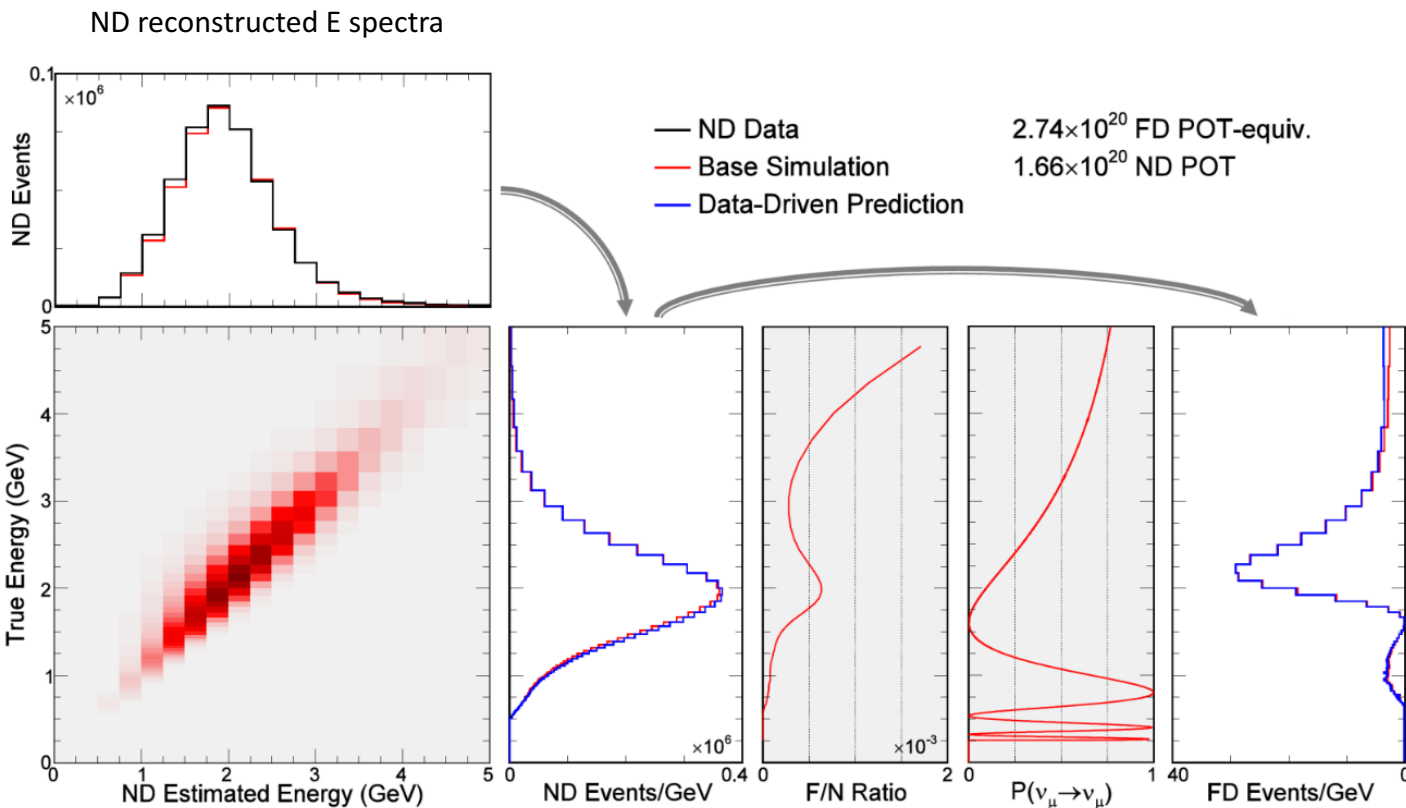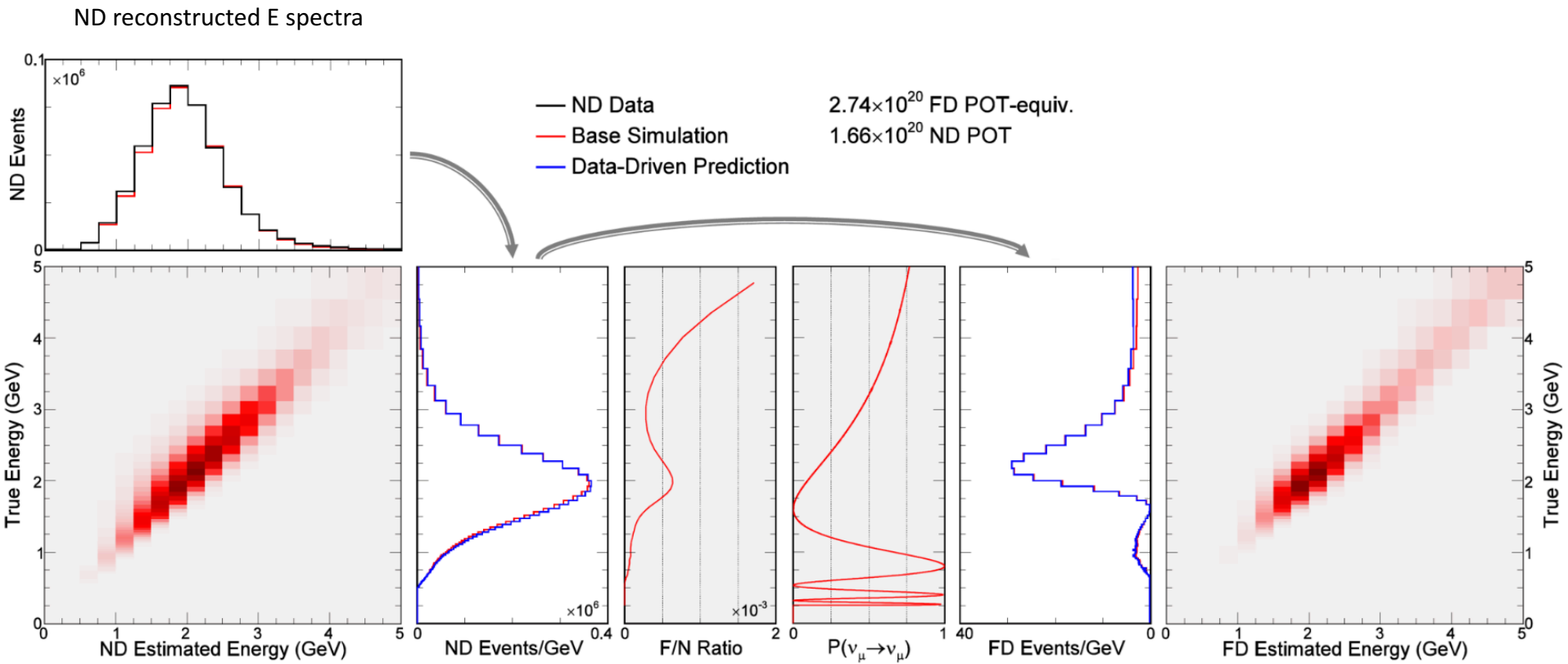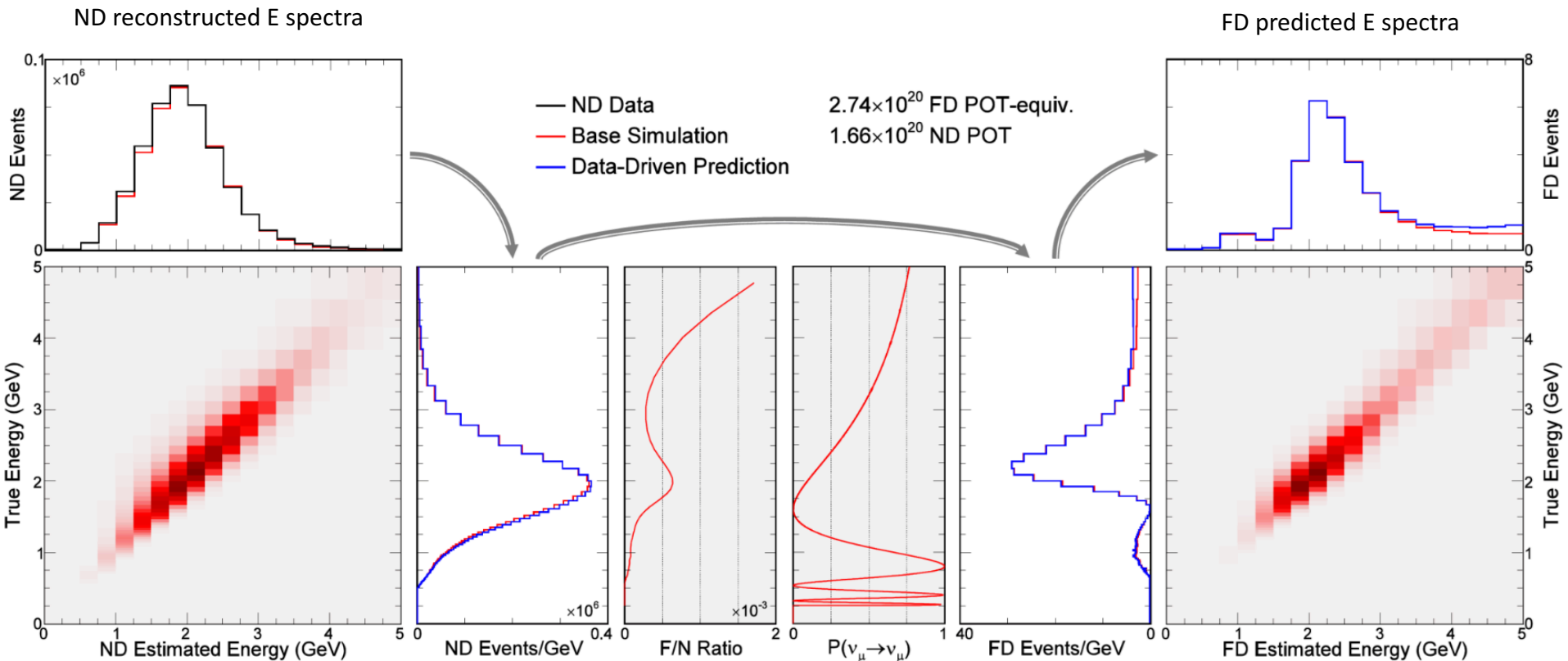**The far detector prediction is generated using a near to far extrapolation process.**

ND reconstructed E spectra

# Far Detector Prediction:

**The far detector prediction is generated using a near to far extrapolation process.**

ND reconstructed E spectra

FD predicted E spectra



- ND Data
- Base Simulation
- Data-Driven Prediction

$2.74 \times 10^{20}$ FD POT-equiv.
$1.66 \times 10^{20}$ ND POT

# Systematics:

- The effect of many large uncertainties is reduced by the near-to-far extrapolation technique (cross sections, beam flux, etc.)

- Systematics were evaluated using specially generated MC samples, and fit by varying the MC based steps in the extrapolation.
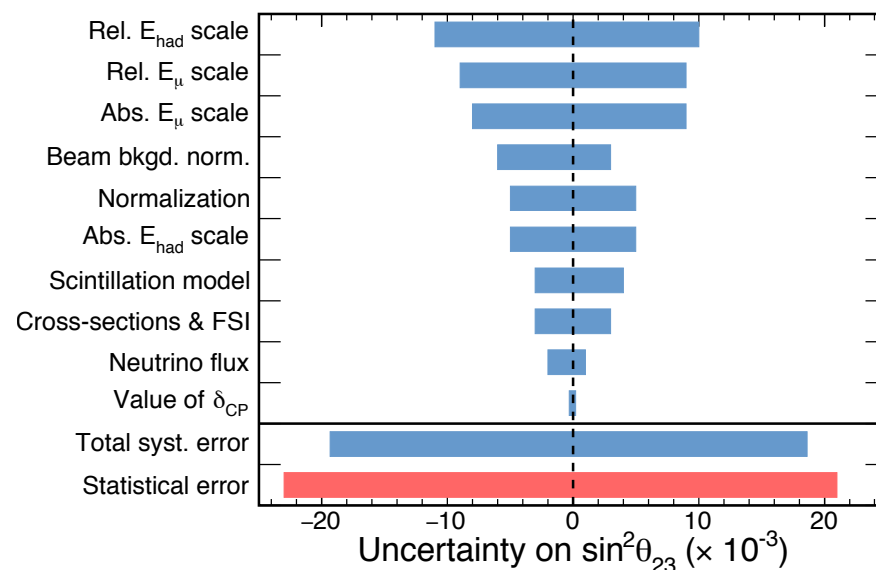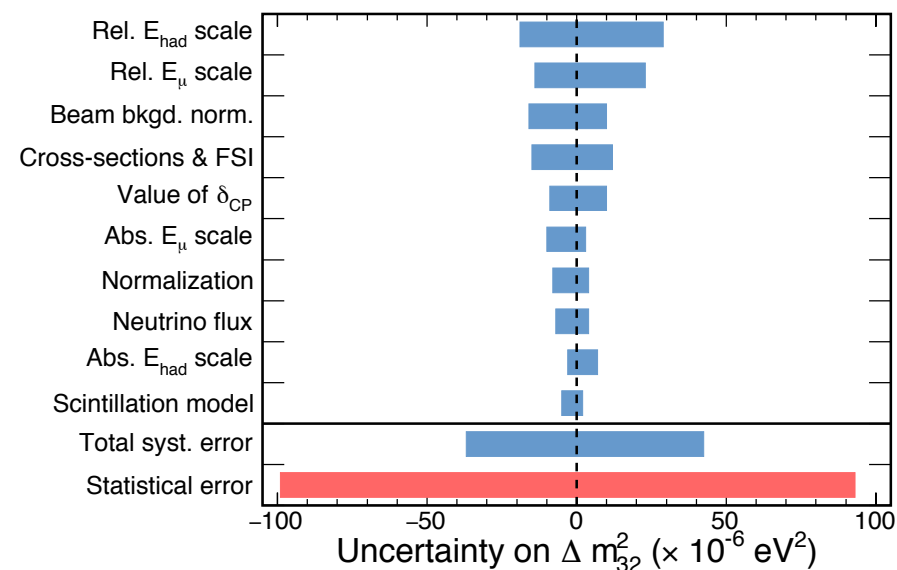
# $v_\mu$ CC Results:

**78 events selected** in the FD
(0 − 5 GeV)

**In the absence of oscillations, 473 events are expected.**

(including 2.9 cosmic and 3.7 beam backgrounds.)

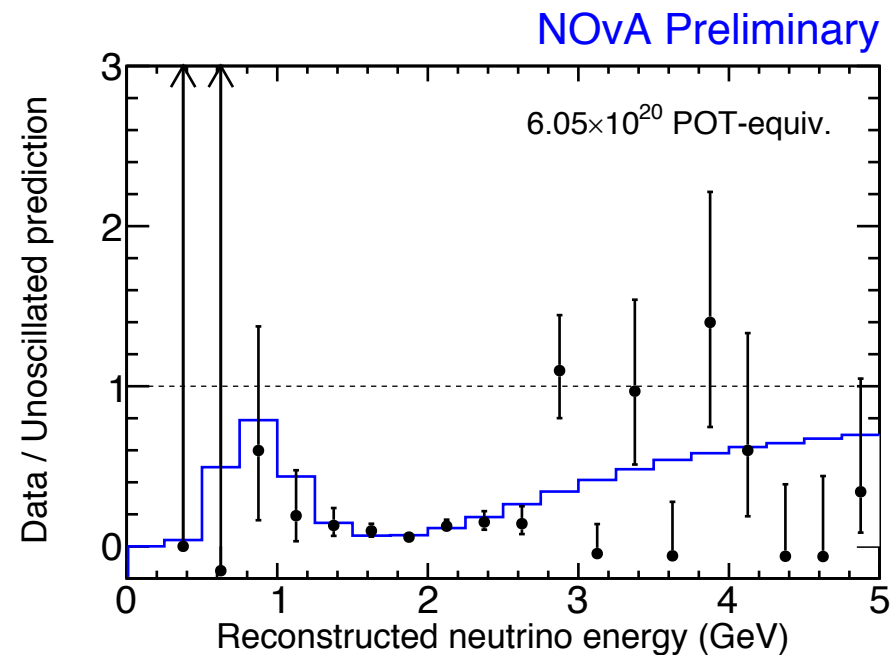## Clear observation of $v_\mu$ disappearance!

# $\nu_\mu$ CC Results:

Spectrum is well matched to the oscillation parameters $\Delta m^2_{32}$ and $\theta_{23}$.

(All syst. uncertainties fit as nuisance parameters.)

Best fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3} \text{eV}^2$$

$$\sin^2 \theta_{23} = 0.404^{+0.030}_{-0.022}(0.624^{+0.022}_{-0.030})$$

**Maximal mixing is disfavored at 2.6σ!**
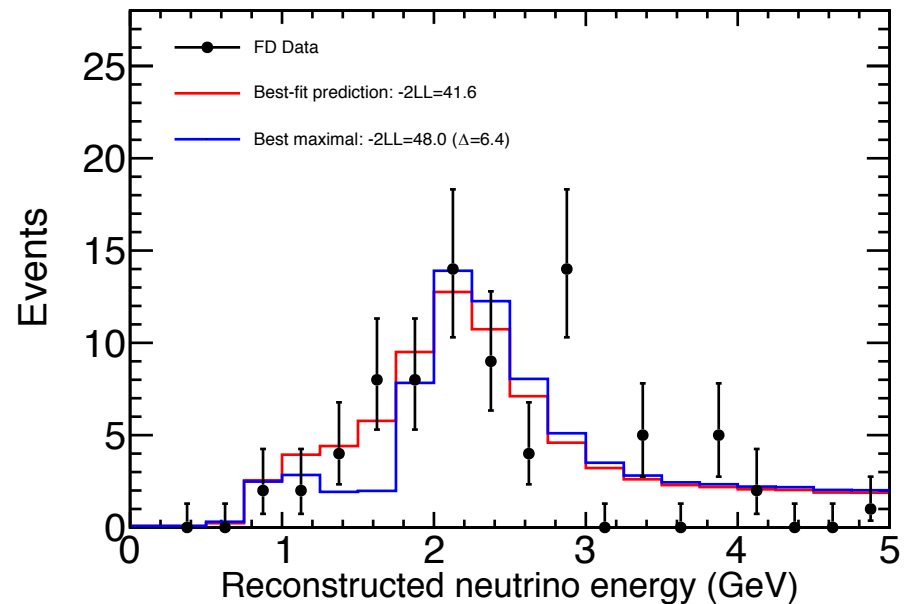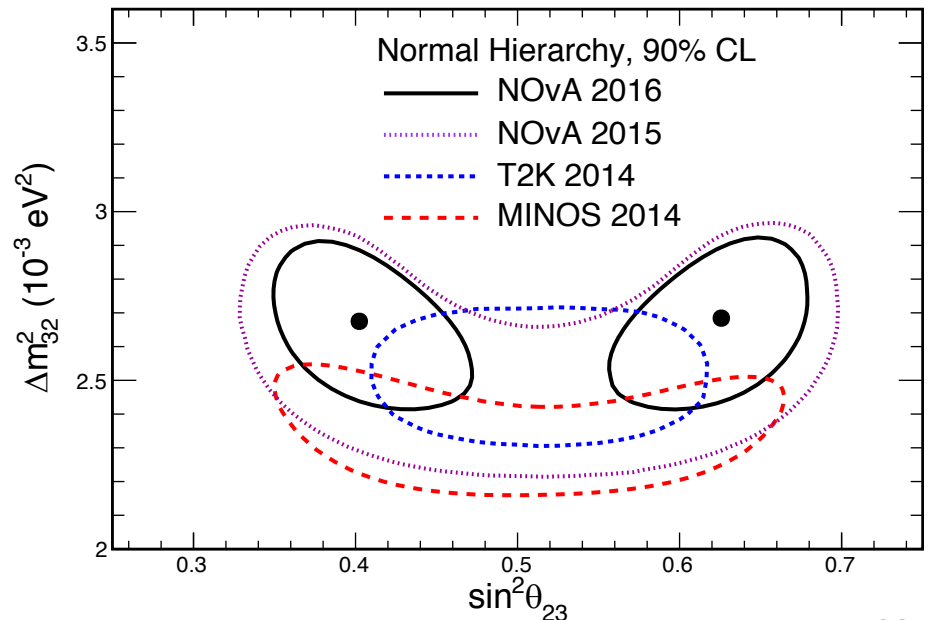
# NOvA Results Summary:

- NOvA is a smoothly running experiment with more exciting physics on the way!

- Unambiguous observation of $\nu_\mu$ disappearance which favors non-maximal mixing:

$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3} \text{ eV}^2$$
$$\sin^2 \theta_{23} = 0.404 \ (+0.030, -0.022)$$

- We have just recently finished a run in anti-neutrino mode.

- **Updated analyses are coming soon!**

www-nova.fnal.gov

# Backups:

# Neutrino Oscillations:

$$\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{bmatrix} \begin{bmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{bmatrix} \begin{bmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

$$S_{ij} \equiv Sin(\theta_{ij}) \quad C_{ij} \equiv Cos(\theta_{ij})$$

- Neutrinos can be described in one of two different bases: flavor or mass.
- Neutrino mixing is described by 3 real rotation angles and a CP violating phase factor, $\delta$.
- All three rotation angles have been measured, but we don't yet know what delta is.

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# Neutrino Oscillations:

         PMNS          mass

$$\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = \begin{bmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23}-C_{12}S_{23}S_{13}e^{i\delta} & C_{12}C_{23}-S_{12}S_{23}S_{13}e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23}-C_{12}C_{23}S_{13}e^{i\delta} & -C_{12}S_{23}-S_{12}C_{23}S_{13}e^{i\delta} & C_{23}C_{13} \end{bmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

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- Neutrinos can be described in one of two different bases: flavor or mass.

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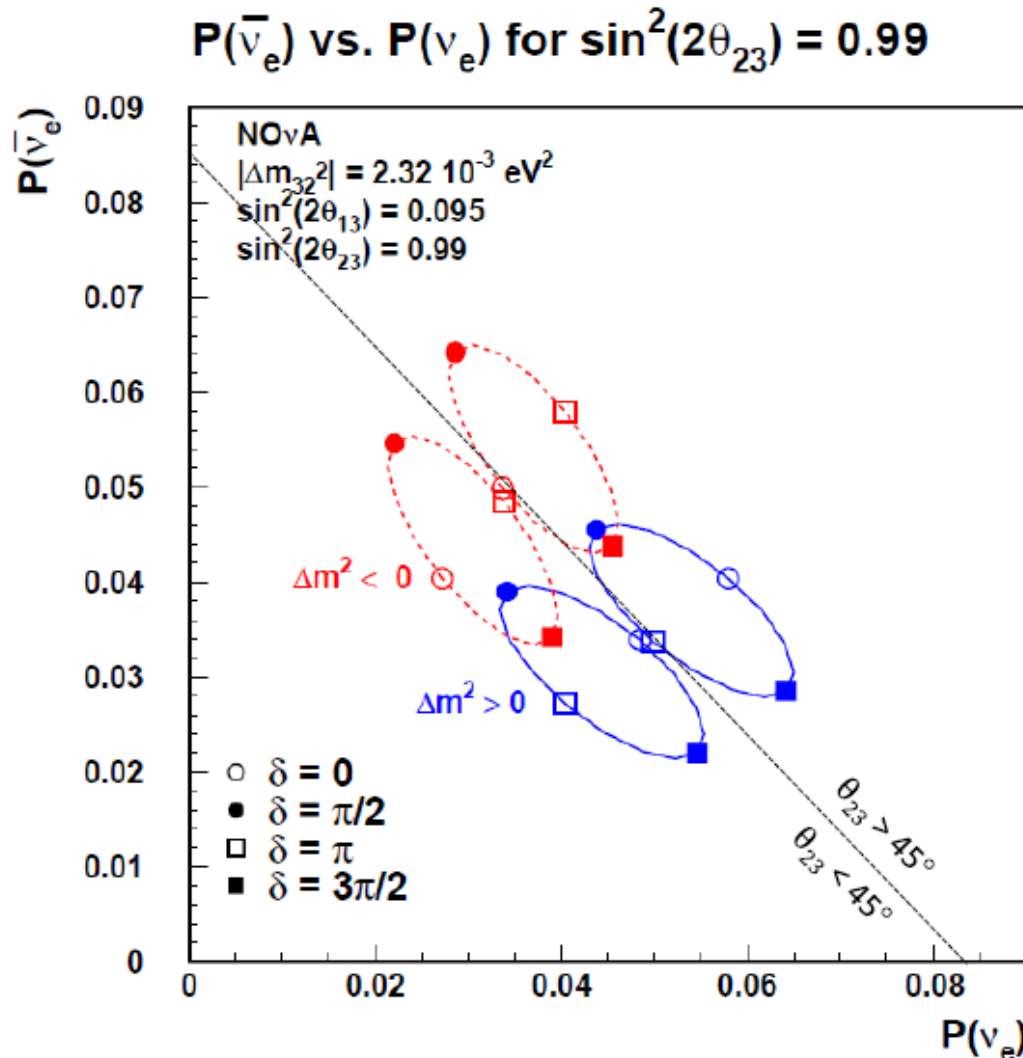- All three rotation angles have been measured, but we don't yet know what delta is.

# Resolving the $\theta_{23}$ Octant:



$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 0.99$

NOvA
$|\Delta m_{32}^2| = 2.32 \; 10^{-3} \; eV^2$
$\sin^2(2\theta_{13}) = 0.095$
$\sin^2(2\theta_{23}) = 0.99$

$\Delta m^2 < 0$

$\Delta m^2 > 0$

$\theta_{23} > 45°$
$\theta_{23} < 45°$

- $\circ$  $\delta = 0$
- $\bullet$  $\delta = \pi/2$
- $\square$  $\delta = \pi$
- $\blacksquare$  $\delta = 3\pi/2$

- **Including CP violation**

- **Including the matter effect**

- **Including non-maximal $\Theta_{23}$**

# Neutrino Oscillations:

**Flavor oscillation in general:**

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\alpha j} U_{\beta j} e^{-i m_j^2 L/2E} \right|^2$$

**$\nu_\mu$ survival probability:**

$$P(\nu_\mu \to \nu_\mu) \approx 1 - sin^2(2\theta_{23}) sin^2 \left( \frac{1.27 \Delta m_{32}^2 L}{E} \right)$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

$\Delta_{23}$

**$\nu_e$ appearance probability:**

$$P\left( \overset{(-)}{\nu_\mu} \to \overset{(-)}{\nu_e} \right) \approx P_{atm} + P_{sol} + 2\sqrt{P_{atm} P_{sol}} [\cos(\Delta_{32}) \cos(\delta) \mp \sin(\Delta_{32}) \sin(\delta)]$$

$$P_{atm} \equiv \sin^2(\Theta_{23}) \sin^2(2\Theta_{13}) \frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2} (\Delta_{31})^2$$

$$P_{sol} \equiv \cos^2(\Theta_{23}) \sin^2(2\Theta_{12}) \frac{\sin^2(\mp aL)}{(\mp aL)^2} (\Delta_{21})^2$$

"−" = neutrinos

"+" = anti − neutrinos

$$a \equiv G_F N_e / \sqrt{2}$$

$N_e$ = electron density in Earth

**octant**

Is $\theta_{23} > 45°$ or $\theta_{23} < 45°$?

**hierarchy**

Is $m_3 > m_1$ or is $m_3 < m_1$?

**CP violation**

Is $\delta \neq 0$?

# Neutrino Oscillations:

**$v_e$ appearance probability:**

$$P\left(\overset{(-)}{v_\mu} \to \overset{(-)}{v_e}\right) \approx P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}\left[\cos(\Delta_{32})\cos(\delta) \mp \sin(\Delta_{32})\sin(\delta)\right]$$

$$P_{atm} \equiv \sin^2(\Theta_{23})\sin^2(2\Theta_{13})\frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2}(\Delta_{31})^2$$
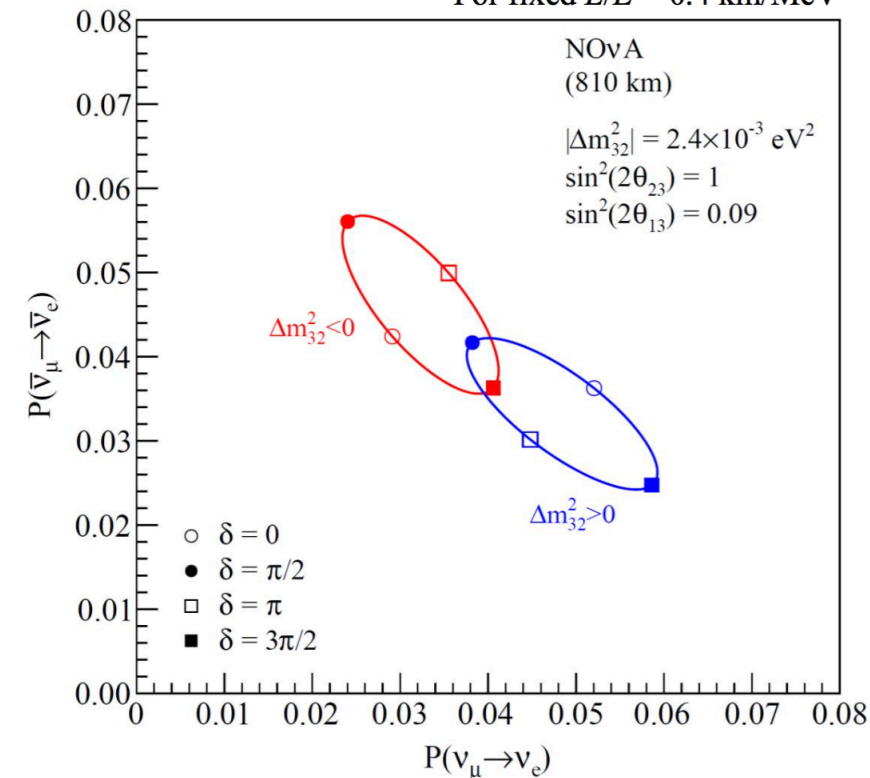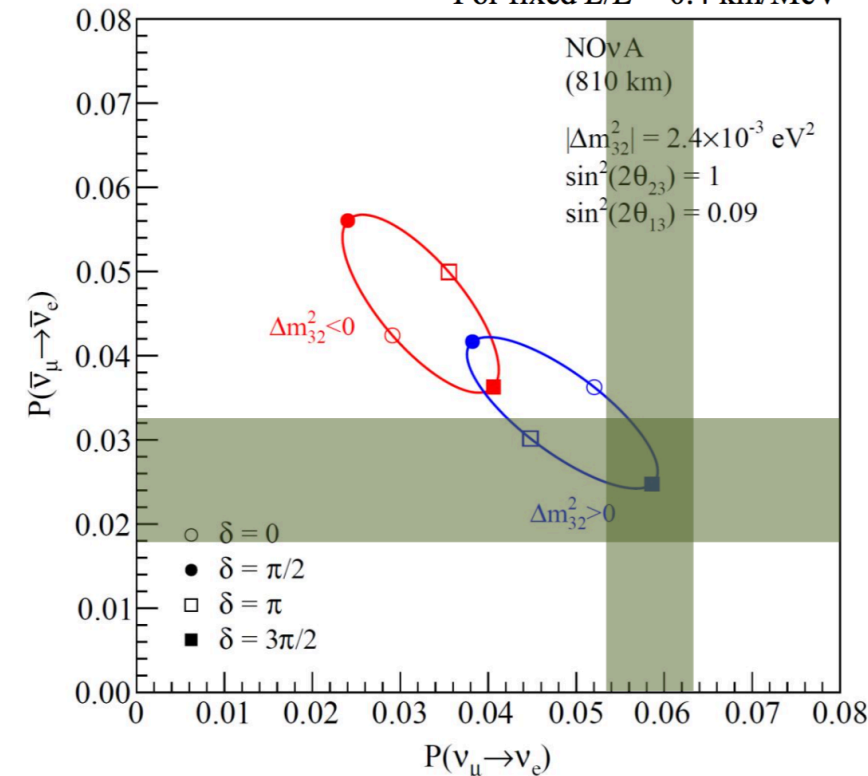
$$P_{sol} \equiv \cos^2(\Theta_{23})\sin^2(2\Theta_{12})\frac{\sin^2(\mp aL)}{(\mp aL)^2}(\Delta_{21})^2$$

$$"-" = neutrinos$$
$$"+" = anti-neutrinos$$
$$a \equiv G_F N_e/\sqrt{2}$$
$$N_e = electron\ density\ in\ Earth$$

For fixed $L/E = 0.4$ km/MeV



NOvA
(810 km)

$|\Delta m_{32}^2| = 2.4 \times 10^{-3}$ eV$^2$
$\sin^2(2\theta_{23}) = 1$
$\sin^2(2\theta_{13}) = 0.09$

$\Delta m_{32}^2 < 0$

$\Delta m_{32}^2 > 0$

○  $\delta = 0$
●  $\delta = \pi/2$
□  $\delta = \pi$
■  $\delta = 3\pi/2$

P($\bar{v}_\mu \to \bar{v}_e$)

P($v_\mu \to v_e$)

# Neutrino Oscillations:

**$v_e$ appearance probability:**

$$P\left(\overset{(-)}{v_\mu} \to \overset{(-)}{v_e}\right) \approx P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}[\cos(\Delta_{32})\cos(\delta) \mp \sin(\Delta_{32})\sin(\delta)]$$

$$P_{atm} \equiv \sin^2(\Theta_{23})\sin^2(2\Theta_{13})\frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2}(\Delta_{31})^2$$

$$P_{sol} \equiv \cos^2(\Theta_{23})\sin^2(2\Theta_{12})\frac{\sin^2(\mp aL)}{(\mp aL)^2}(\Delta_{21})^2$$

$"-" = neutrinos$

$"+" = anti-neutrinos$

$a \equiv G_F N_e/\sqrt{2}$

$N_e = electron\ density\ in\ Earth$

For fixed $L/E = 0.4$ km/MeV



NOvA (810 km)

$|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV$^2$
$\sin^2(2\theta_{23}) = 1$
$\sin^2(2\theta_{13}) = 0.09$

$\Delta m^2_{32} < 0$

$\Delta m^2_{32} > 0$

○ $\delta = 0$
● $\delta = \pi/2$
□ $\delta = \pi$
■ $\delta = 3\pi/2$

y-axis: $P(\bar{v}_\mu \to \bar{v}_e)$
x-axis: $P(v_\mu \to v_e)$

**A simultaneous measurement of $v_e$ appearance and $\overline{v}_e$ appearance will help us answer these open questions!**
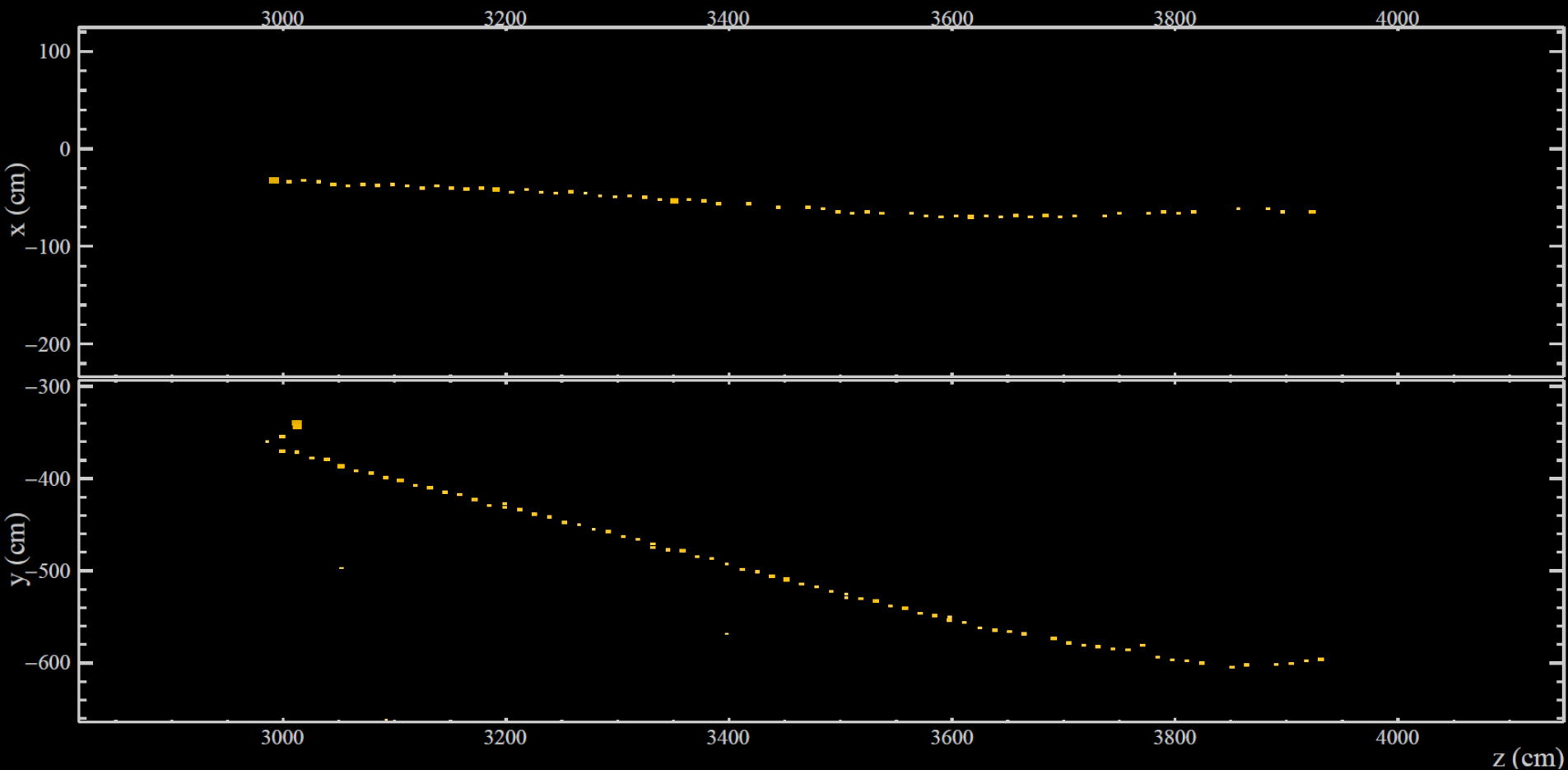
# The NOvA Experiment: NuMI Beam

**The NOvA experiment is 14 mrad off-axis:**

- gives us a narrowly peaked *v* energy spectrum at 2 GeV
- 2 GeV = oscillation max for 810 km
- helps reduce NC backgrounds



NOvA Simulation
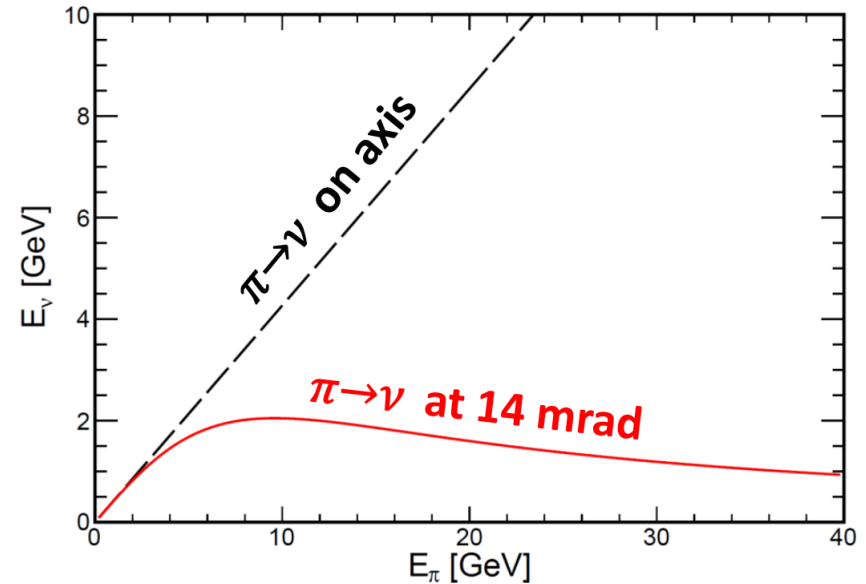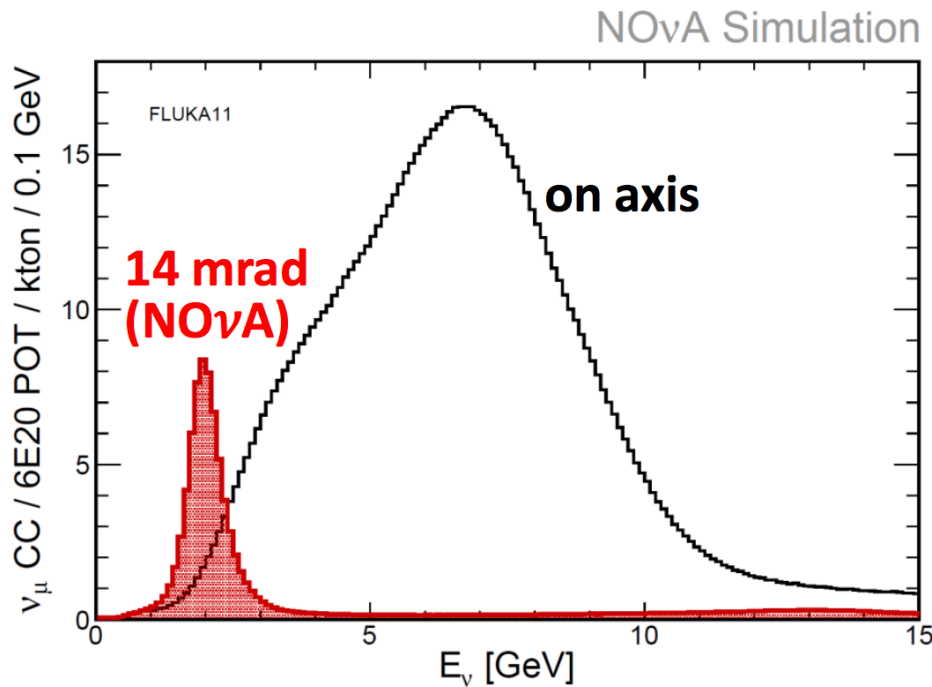


$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$
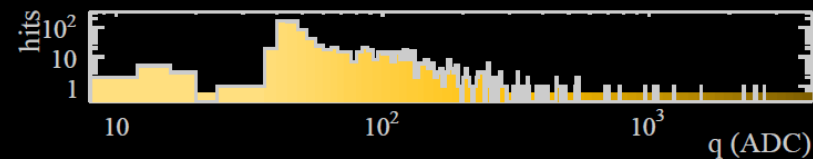
# Far Detector selected $\nu_\mu$ CC candidate
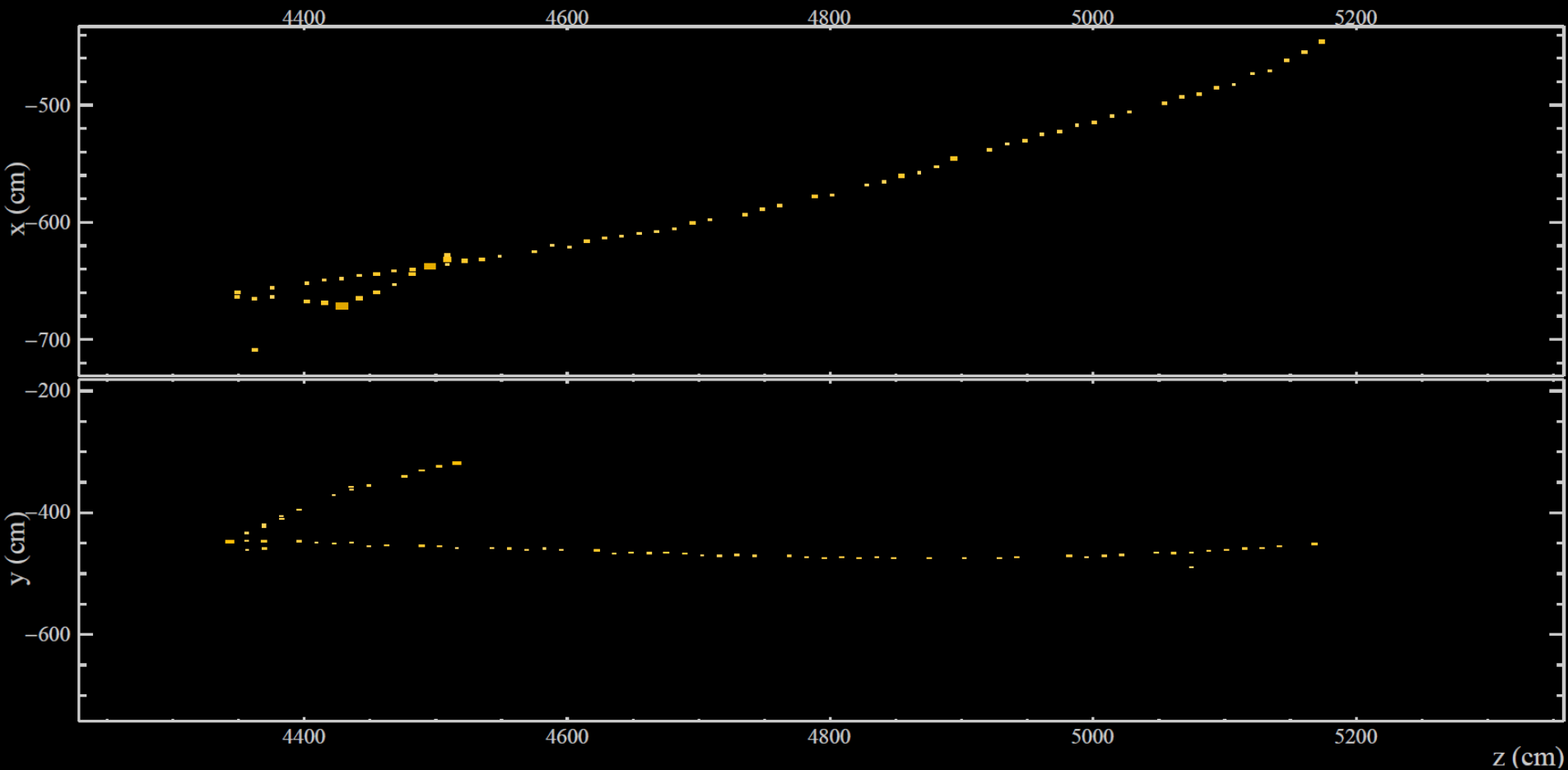


NOvA - FNAL E929

Run:   18756 / 37
Event: 597960 / --

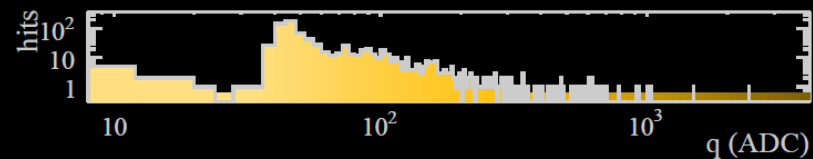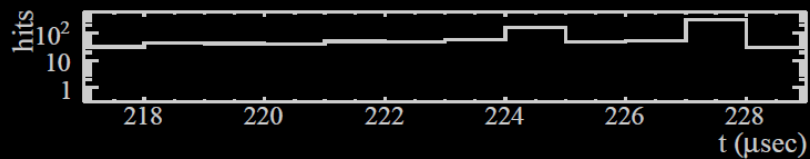UTC Sun Jan 25, 2015
13:29:18.710709824

# Far Detector selected $\nu_\mu$ CC candidate



NOvA - FNAL E929

Run: 18791 / 48
Event: 765587 / --

UTC Fri Jan 30, 2015
07:19:18.516289184
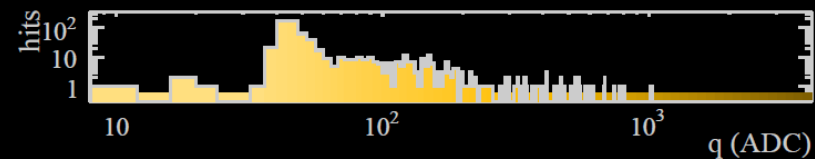
# Far Detector selected $\nu_\mu$ CC candidate
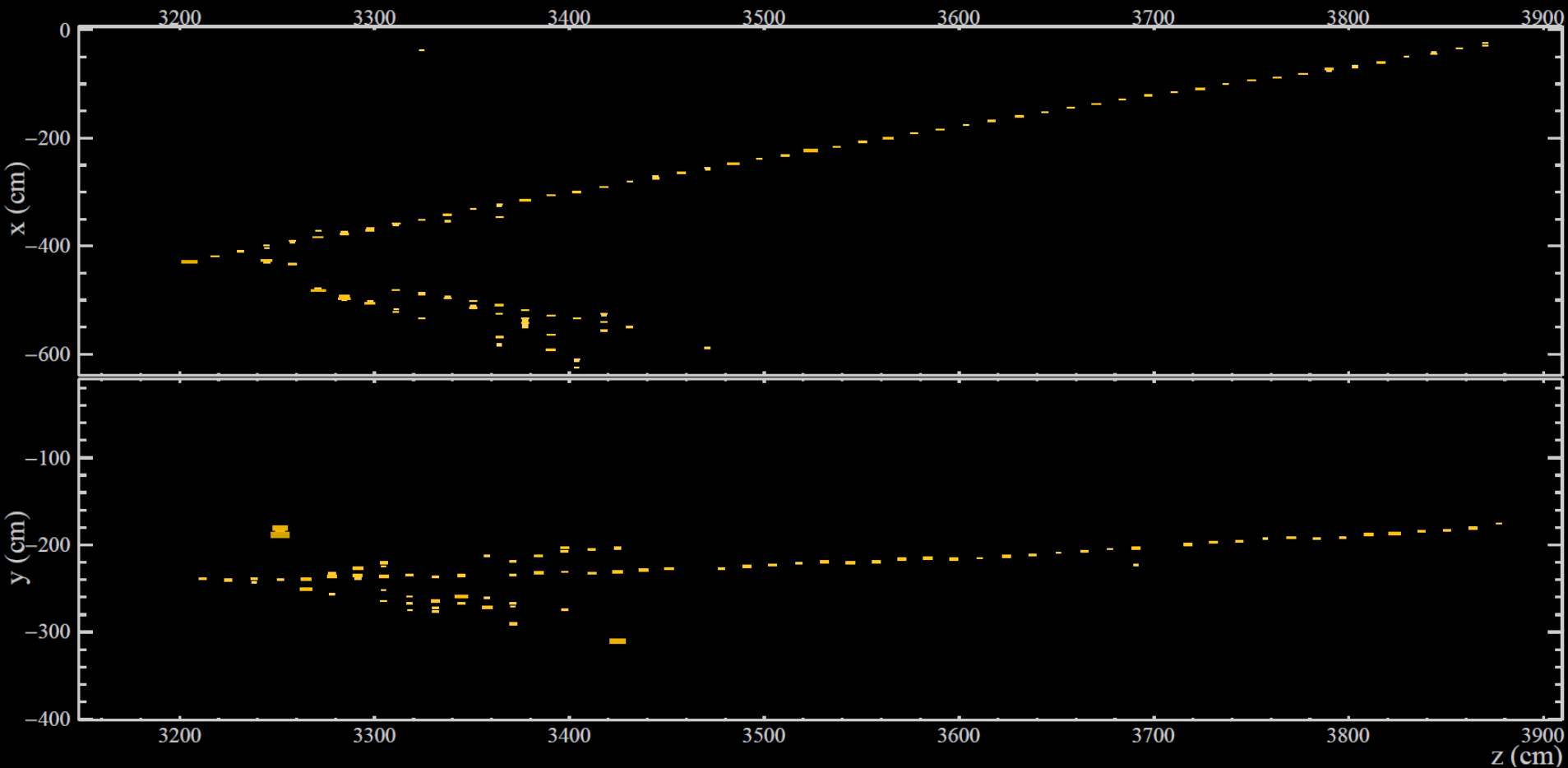
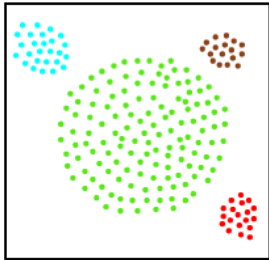

NOvA - FNAL E929
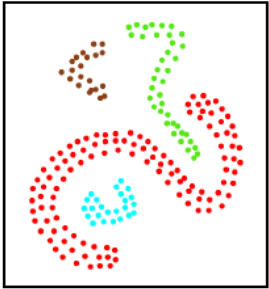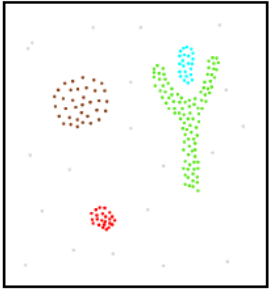
Run: 19084 / 62
Event: 908450 / --
UTC Thu Mar 12, 2015
04:16:51.818581248

# Event Reconstruction with NOvA:

## Clustering:



- Uses an expanding density based clustering algorithm called DBSCAN*

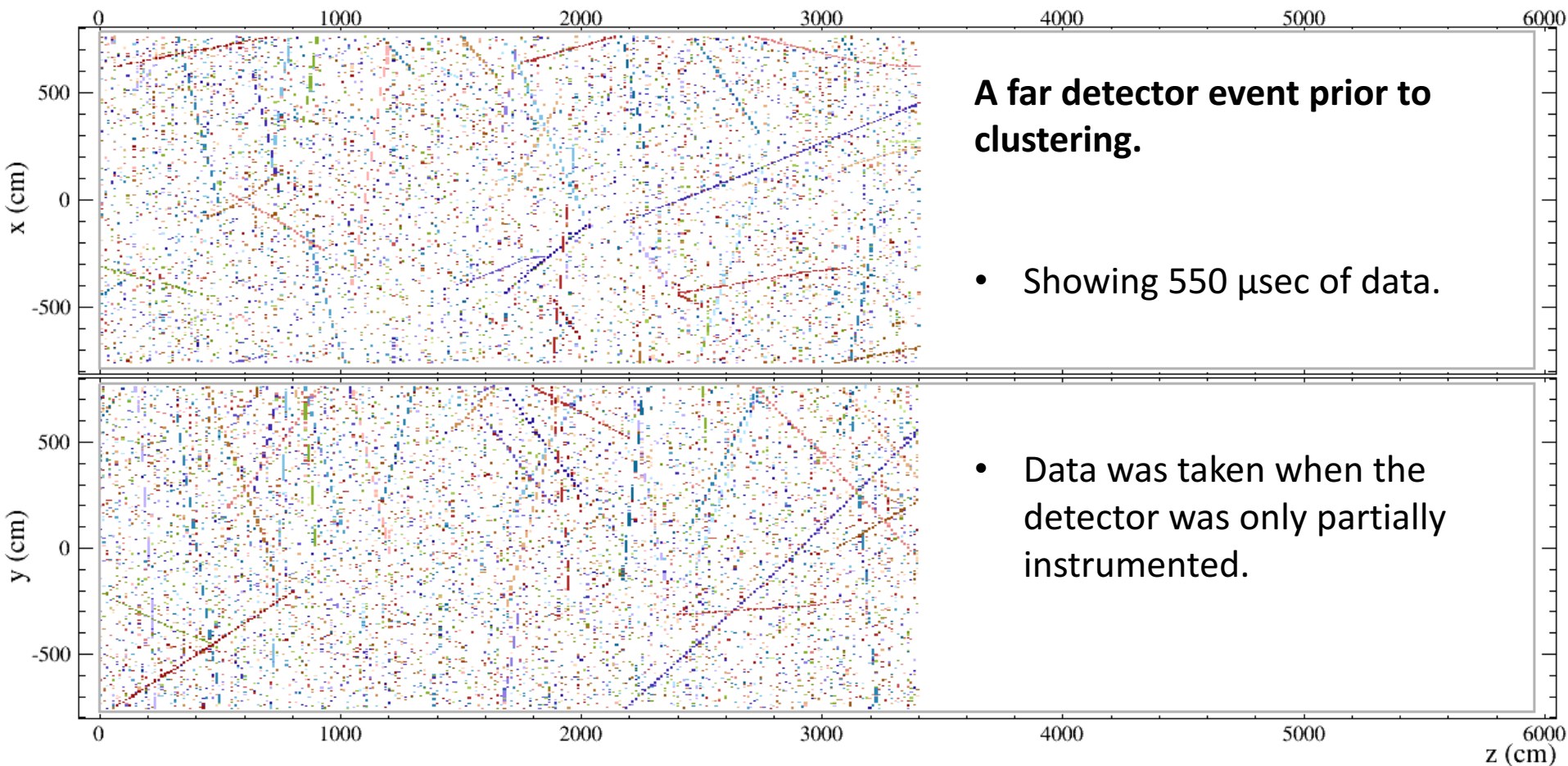- Hits are clustered based on a causality score (two hits are neighbors if their score is < threshold.)

$$score = \left(\frac{\Delta T - \Delta r / c}{T_{res}}\right)^2 + \left(\frac{\Delta r}{D_{pen}}\right)^2$$

- Cluster borders are defined by regions where the neighborhood density drops below some critical value.

- The algorithm expands from neighbor to neighbor to find all borders.

Far Detector:      ave. completeness = ~99%      ave. purity = ~99%
Near Detector:      ave. completeness = ~94%      ave. purity = ~99%
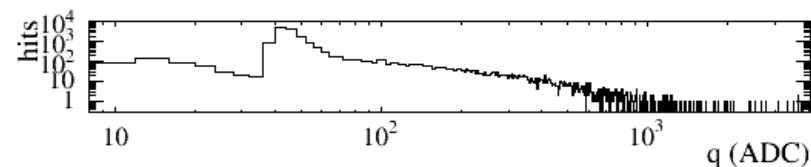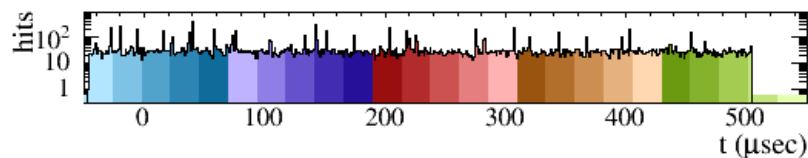
*   M. Ester, et. al., A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise (1996)
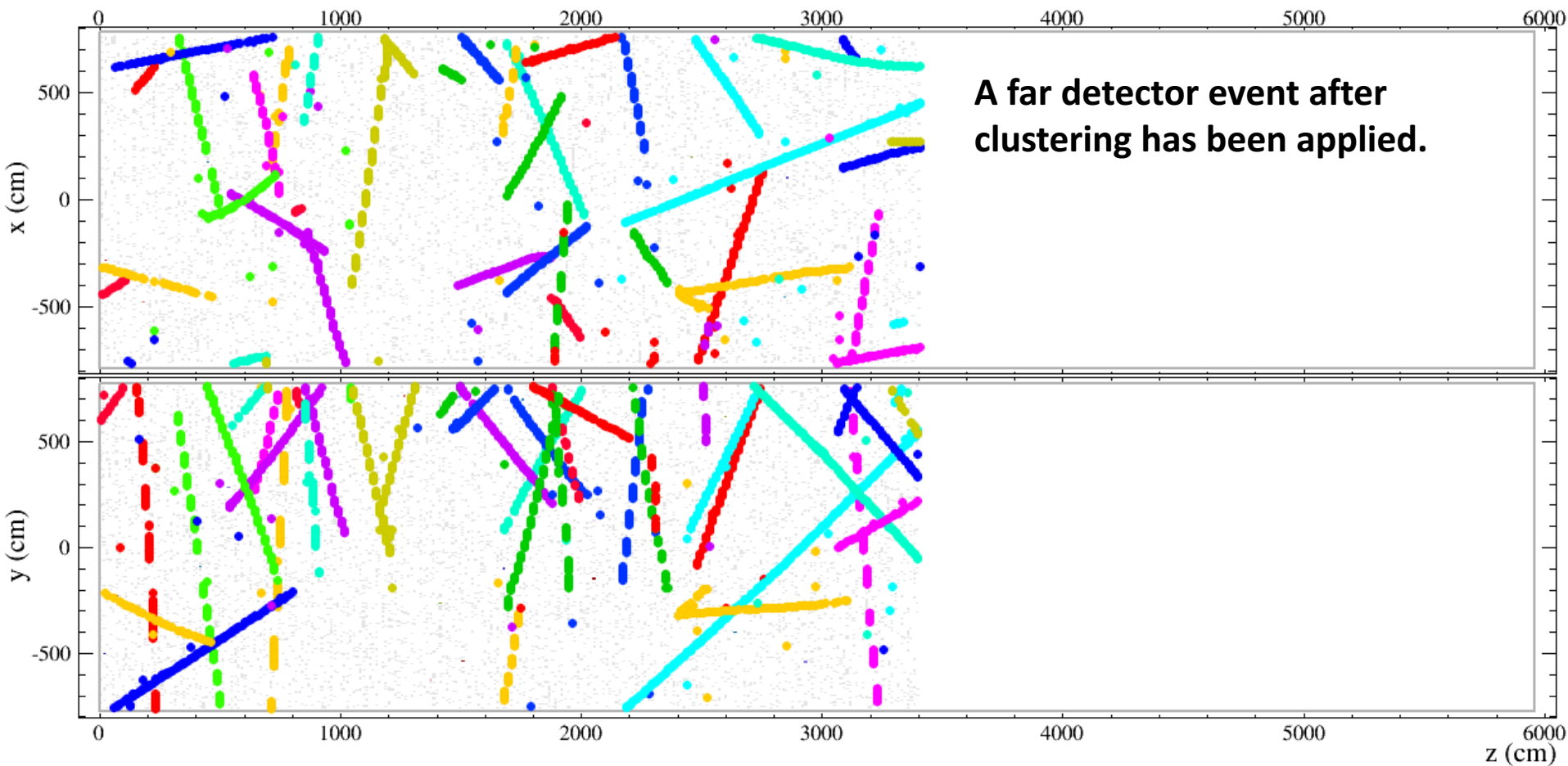
# Event Reconstruction with NOvA:



**A far detector event prior to clustering.**

- Showing 550 μsec of data.

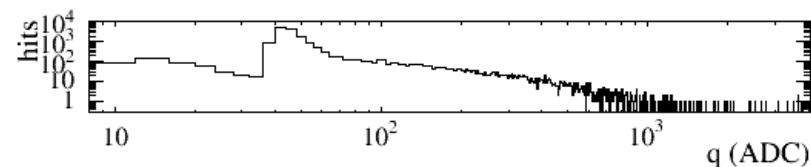- Data was taken when the detector was only partially instrumented.
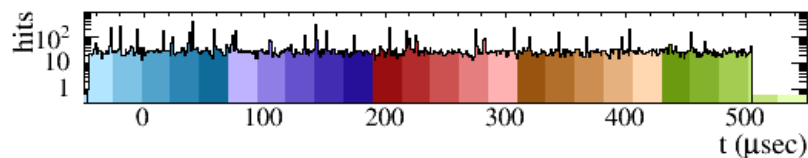
NOvA - FNAL E929

Run: 14828 / 38
Event: 192569 / NuMI
UTC Tue Apr 22, 2014
21:41:51.422846016

40

# Event Reconstruction with NOvA:
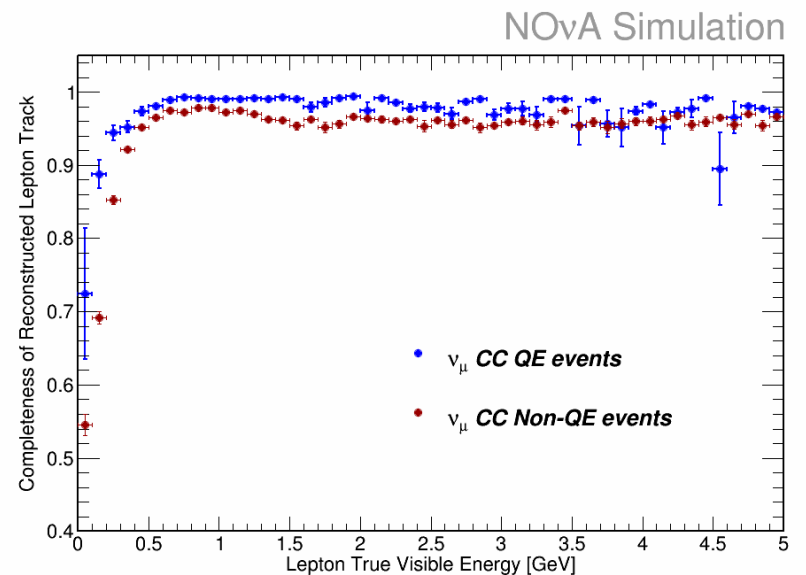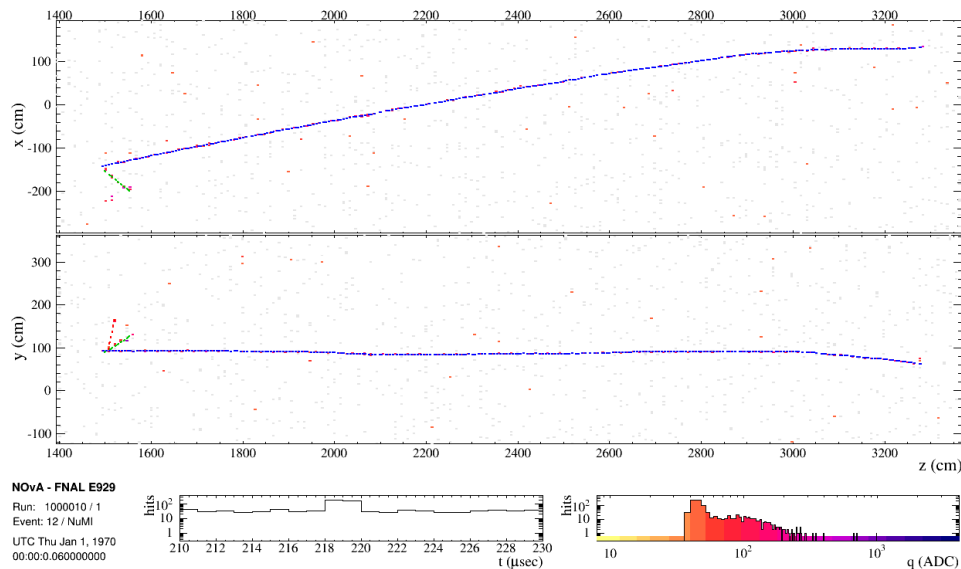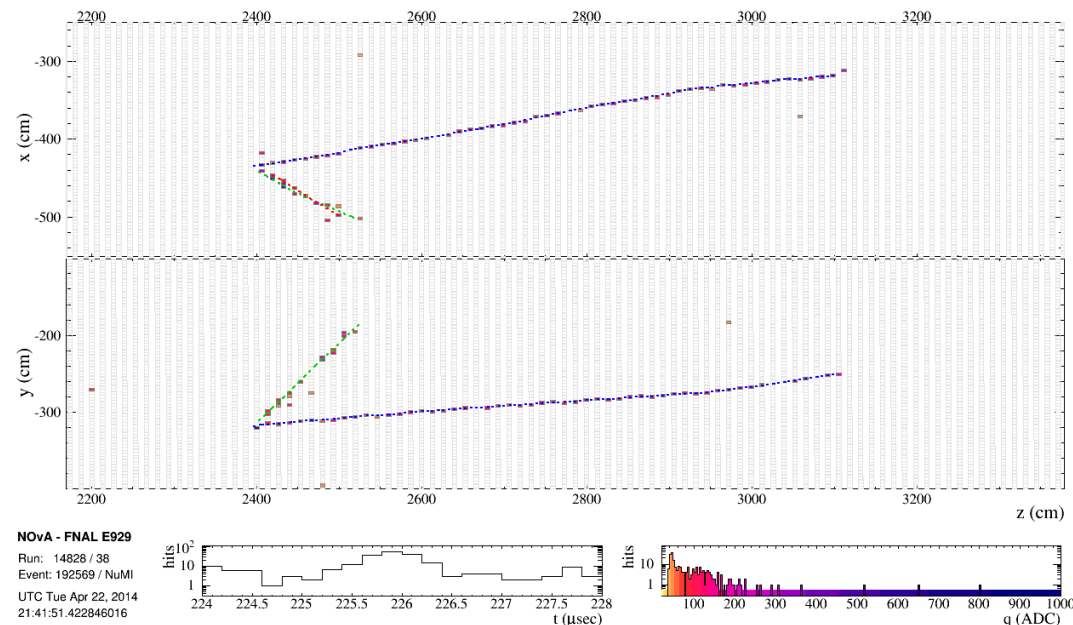
A far detector event after clustering has been applied.

# Event Reconstruction with NOvA:

**Particle Tracking:**

- A tracking algorithm is used primarily to reconstruct muons.

- Tracks are propagated "upstream" in the beam based on a Kalman filter and using a multiple scattering model.

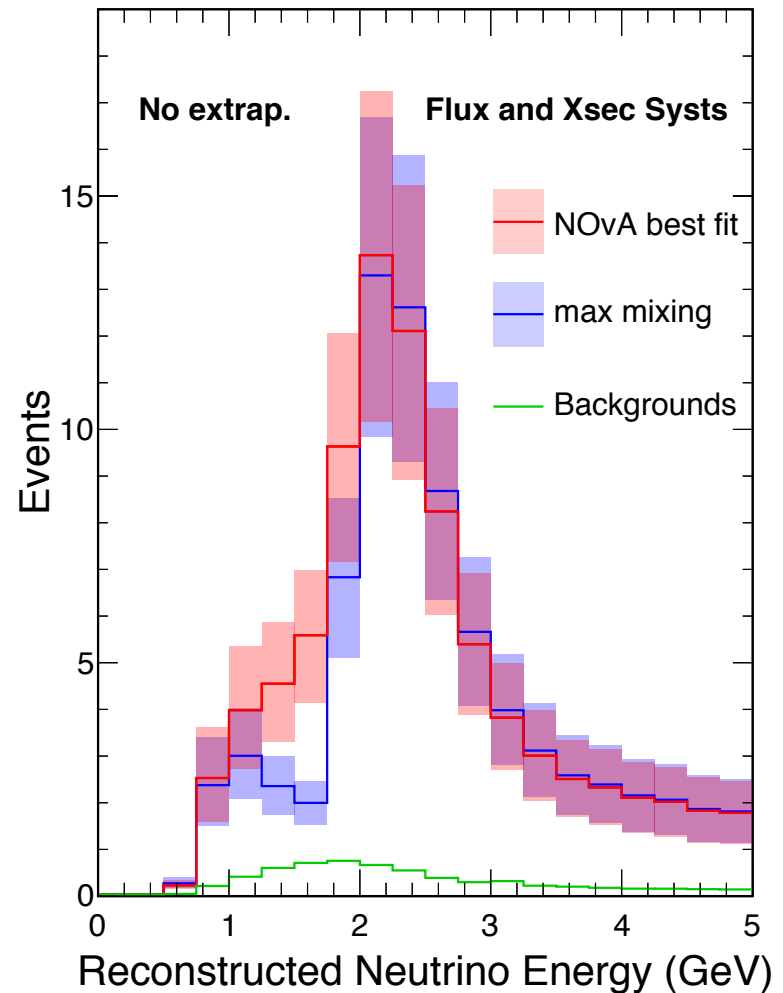# Far Detector Prediction:



NOvA Simulation

NOvA Simulation

**Full extrap. using ND MC**

**Flux and Xsec Systs**

**No extrap.**

**Flux and Xsec Systs**

- NOvA best fit
- max mixing
- Backgrounds

Events

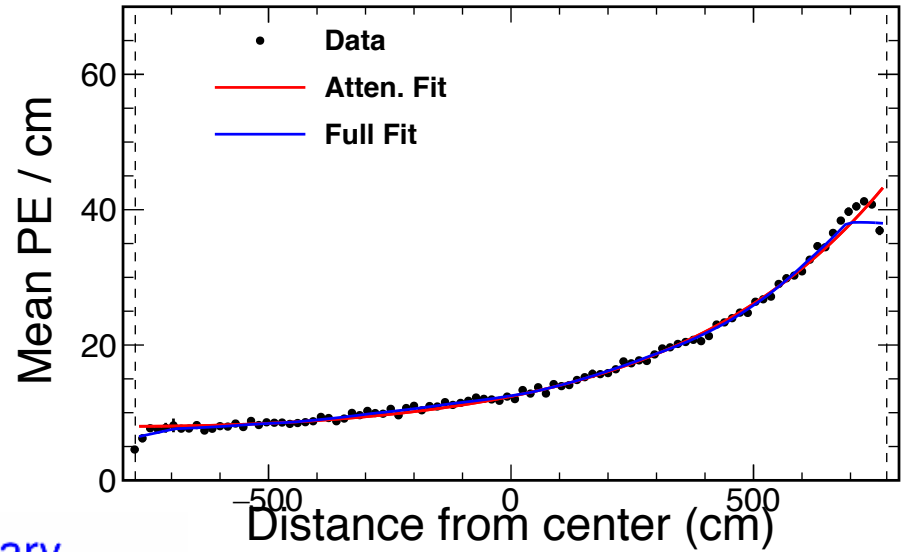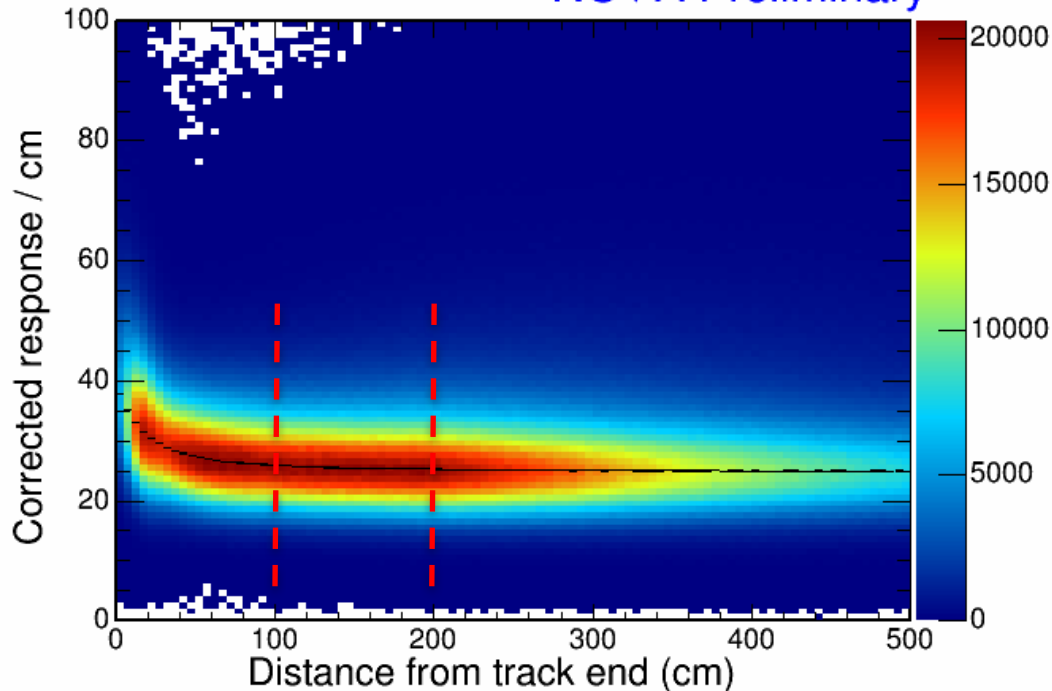Reconstructed Neutrino Energy (GeV)
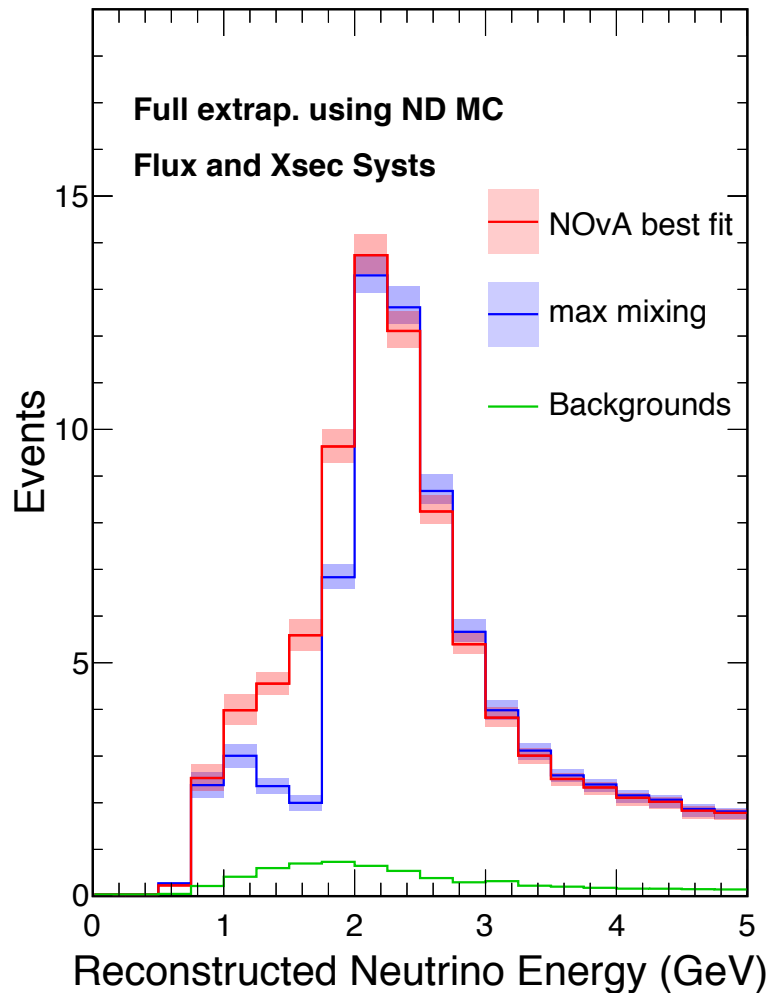
# Calibration:

- Compute the attenuation curve for each fiber individually using through-going cosmic muons.

- This puts all fibers and cells on an equal footing.
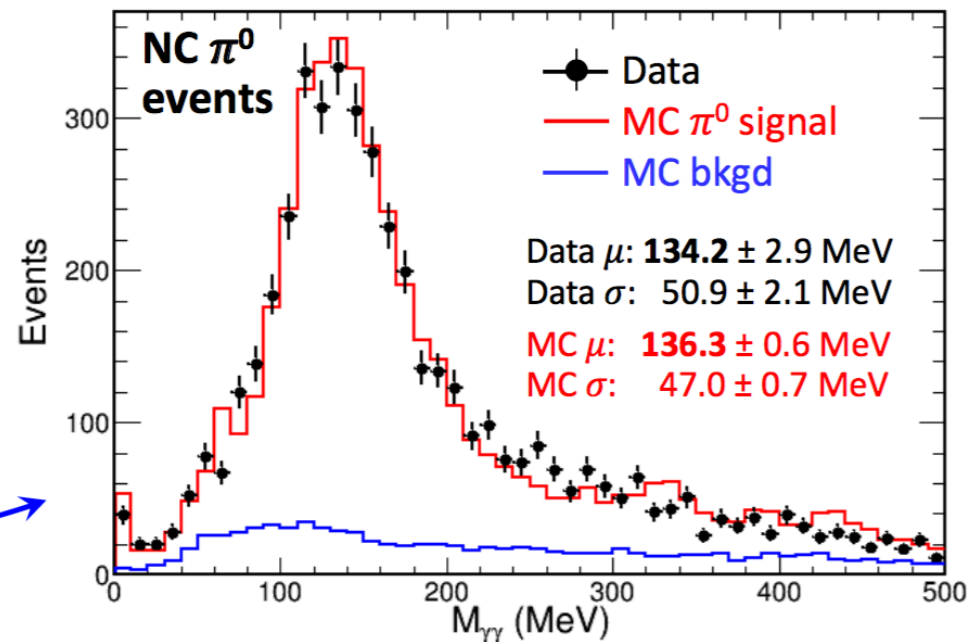
FD cosmic data - plane 49 (vertical), cell 91



- Compute the absolute energy scale for the whole detector using stopping cosmic muons.

- Look for "good" hits in the MIP region of the track.



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# Multiple probes of energy scale

## In Near Detector

- cosmic $\mu$ $dE/dx$ [~vertical]
- beam $\mu$ $dE/dx$ [~horizontal]
- Michel $e^-$ spectrum
- $\pi^0$ mass
- hadronic shower $E$-per-hit

## In Far Detector

- cosmic $\mu$ $dE/dx$ [~vertical]
- beam $\mu$ $dE/dx$ [~horizontal]
- Michel $e^-$ spectrum

**All agree within ±5%**



NC $\pi^0$ events

- Data
- MC $\pi^0$ signal
- MC bkgd

Data $\mu$: **134.2** ± 2.9 MeV
Data $\sigma$: 50.9 ± 2.1 MeV
MC $\mu$: **136.3** ± 0.6 MeV
MC $\sigma$: 47.0 ± 0.7 MeV

$M_{\gamma\gamma}$ (MeV)



ND, 1.66×10²⁰ POT — NOvA Preliminary

$\nu_\mu$ CC events

- Simulated $\nu_\mu$ CC
- Simulated Background
- Data

Average Hadronic Energy Per Hit (GeV)
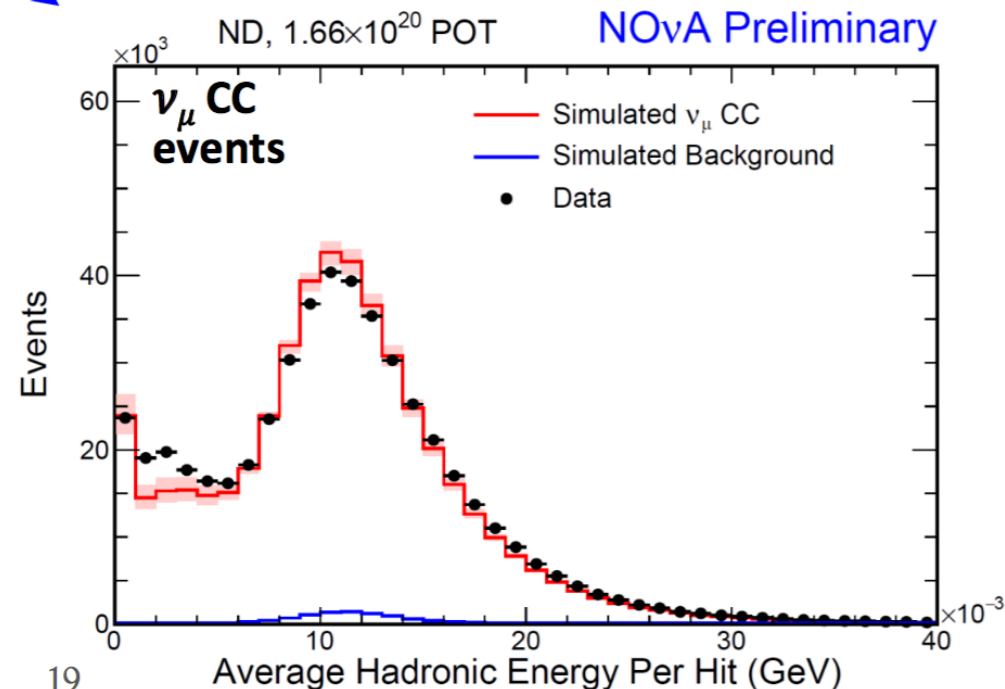
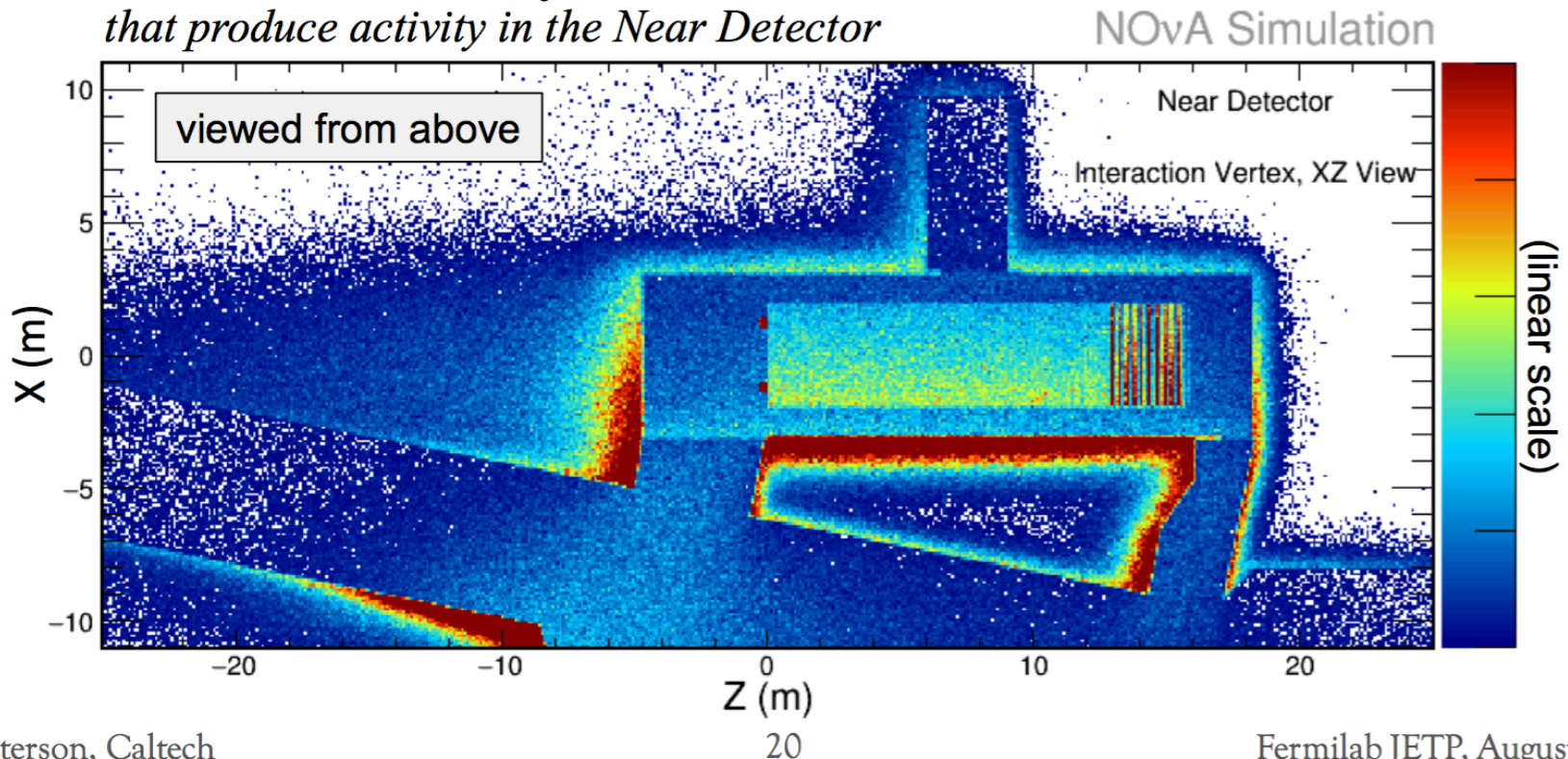# Highly detailed end-to-end simulation chain

- Beam hadron production, propagation; neutrino flux: **FLUKA/FLUGG**
- Cosmic ray flux: **CRY**
- Neutrino interactions and FSI modeling: **GENIE**
- Detector simulation: **GEANT4**
- Readout electronics and DAQ: **Custom simulation routines**

*Simulation: Locations of neutrino interactions that produce activity in the Near Detector*

# Event Reconstruction with NOvA:

**Reconstruction Flow:**

1. Separate physics hits into groups that have a common origin (neutrino interaction or cosmic ray) while also separating them from noise hits. These groups are called "slices."

2. Identify the global event vertex.

3. Create clusters of hits belonging to particles.

4. Make tracks from these clusters using a multiple scattering model.

2. Apply alternate trackers (a Kalman filter and a simple straight-line fitter) used for event selection and cosmic rejection.

# Event Reconstruction with NOvA:

## Finding a Global Vertex:
## (M.Baird, M.Messier, E.Niner)

- A modified two-point Hough transform is used to create a set of 2D lines that reflect major event features. *

- The Hough lines are then used as input to the vertex finding algorithm.

- For a generated list of vertex candidates, the best vertex is the one that minimizes an "energy cost" function based on distances from hits to "arms." **

- A process of simulated annealing is used to allow the best vertex candidate to settle into an optimal location.
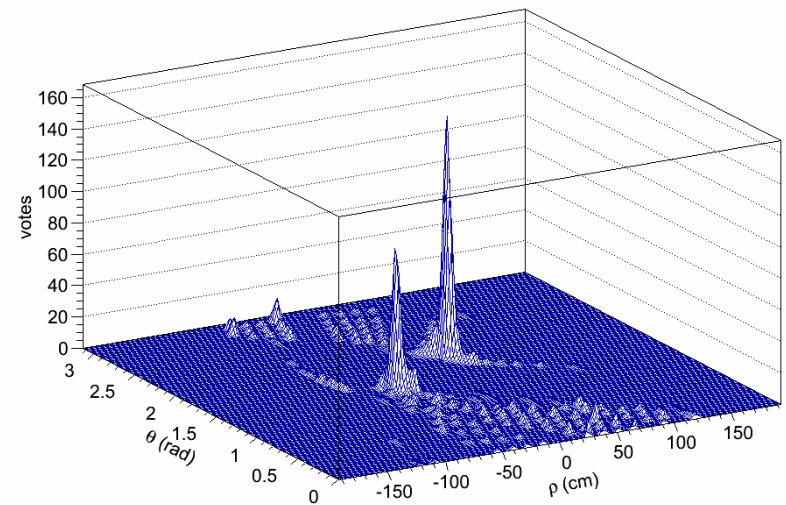


For $v_e$ CC, average vtx. res. = 10.9 cm
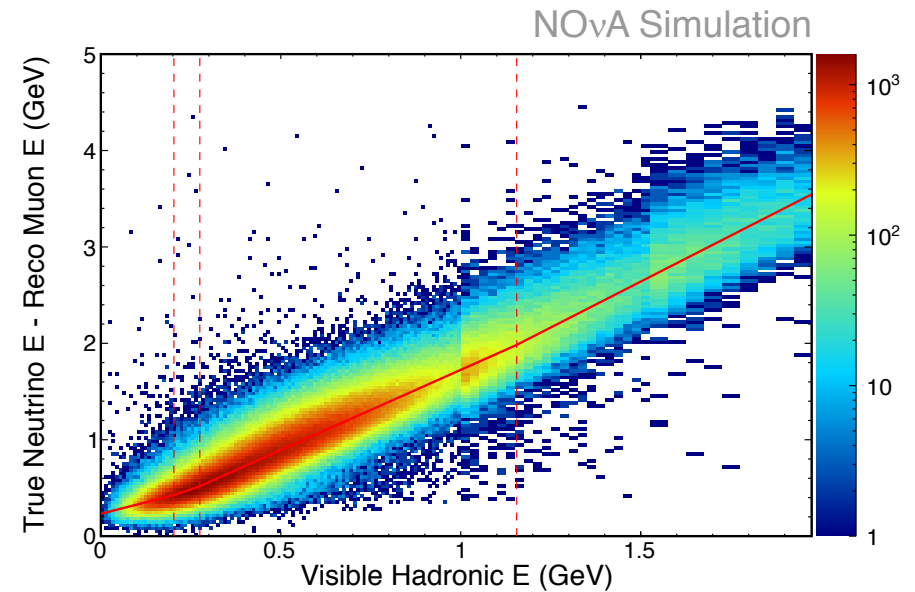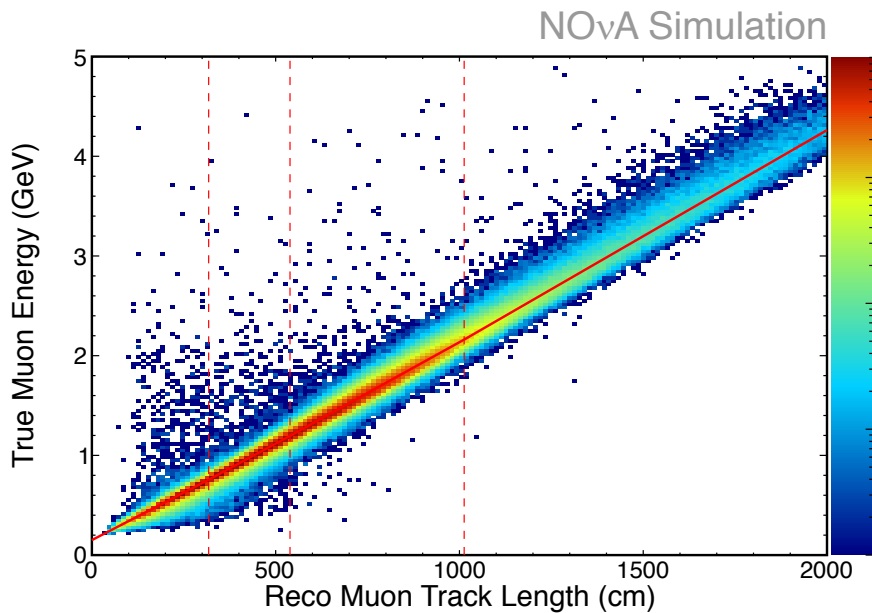For $v_\mu$ CC, average vtx. res. = 11.6 cm
For NC, average vtx. res. = 28.8 cm

*  L. Fernandes and M. Oliveira, Pattern Recognition, 41 (2008) 299-314.

**  M. Ohlsson, C. Peterson, Computer Physics Communications, 71 (1992) 77-98.
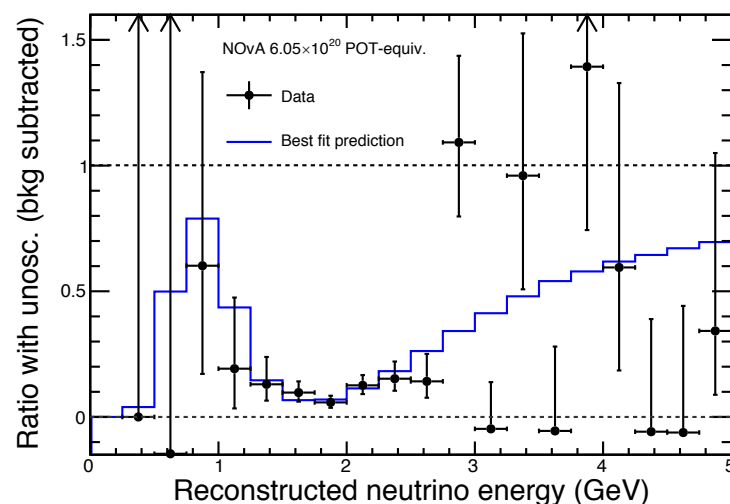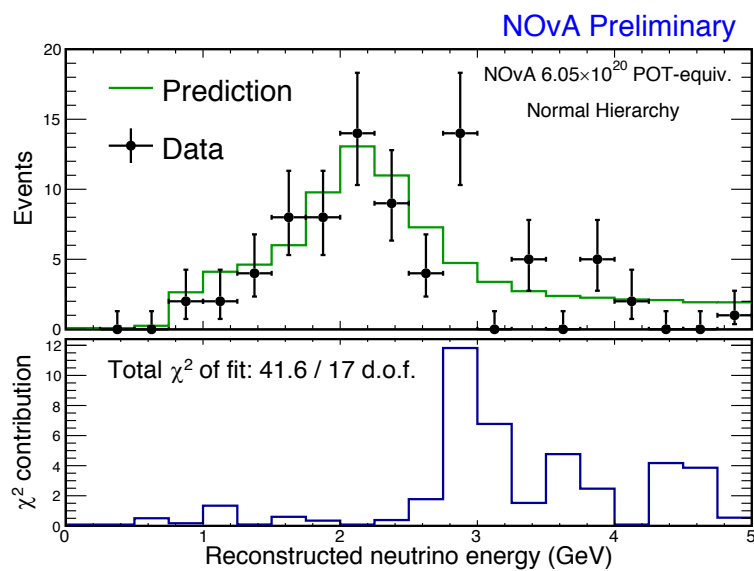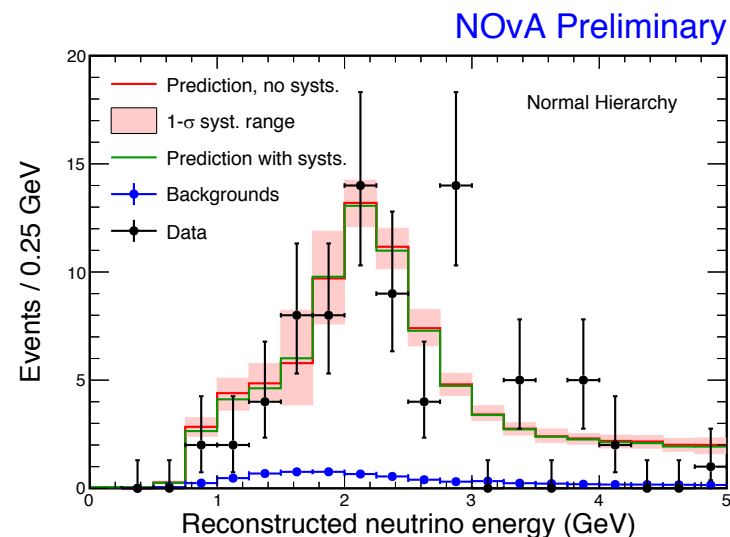
# Energy Estimation:

- True energy for the muon and the hadronic component are converted from track length and summed calorimetric energy (respectively) using the MC.

# Muon Neutrino FD Data

- 78 events observed in FD
  - 473±30 with no oscillation
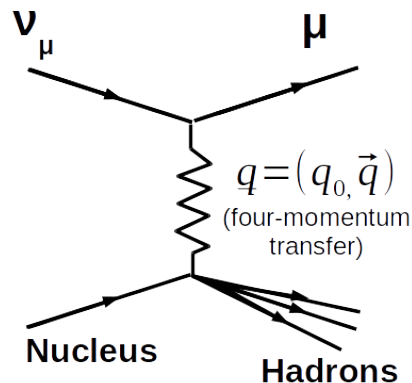  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

$\chi^2$/NDF=41.6/17
Driven by fluctuations in
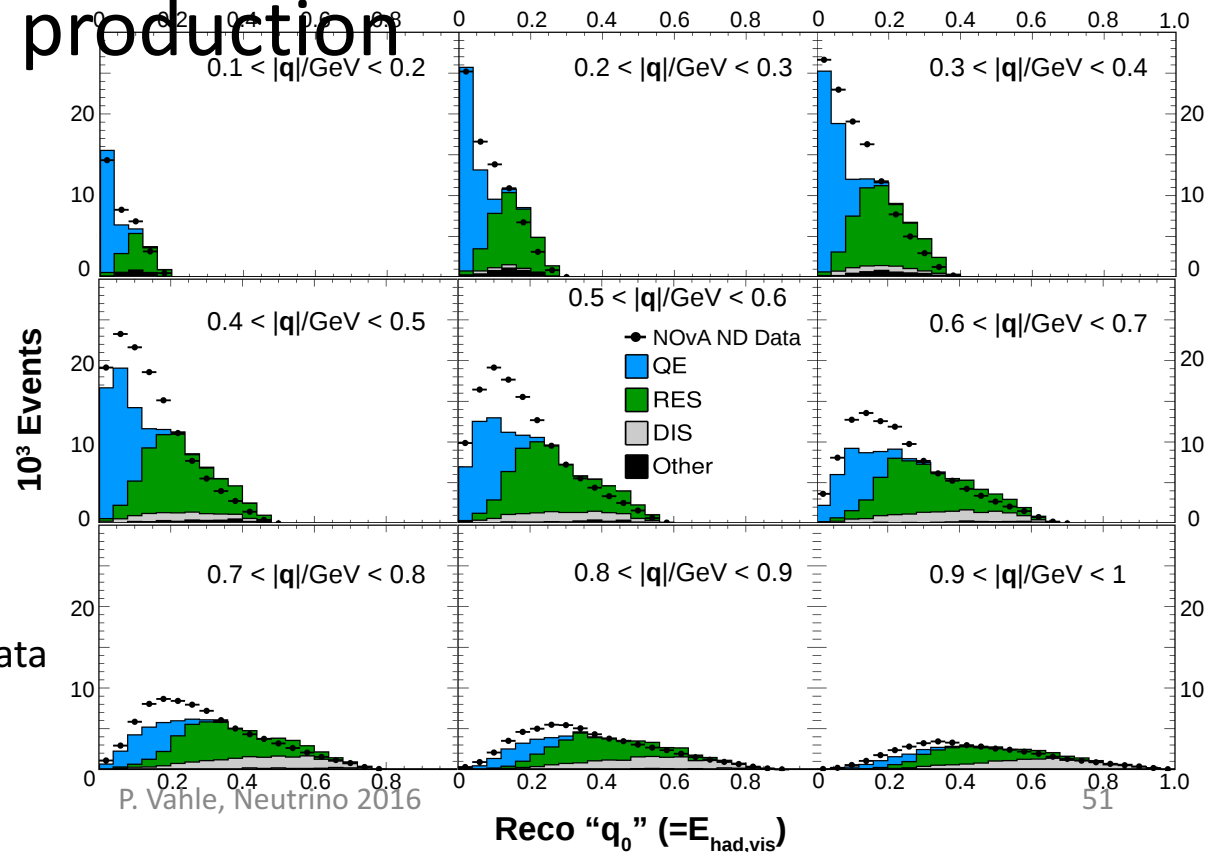tail, no pull in oscillation fit

# Scattering in a Nuclear Environment

- Near detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production

NOvA Preliminary

$q = (q_0, \vec{q})$
(four-momentum transfer)

ν$_\mu$  μ

**Nucleus**  **Hadrons**

Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802



$10^3$ **Events**

| 0.1 < |q|/GeV < 0.2 | 0.2 < |q|/GeV < 0.3 | 0.3 < |q|/GeV < 0.4 |
| 0.4 < |q|/GeV < 0.5 | 0.5 < |q|/GeV < 0.6 | 0.6 < |q|/GeV < 0.7 |
| 0.7 < |q|/GeV < 0.8 | 0.8 < |q|/GeV < 0.9 | 0.9 < |q|/GeV < 1 |

NOvA ND Data
QE
RES
DIS
Other

**Reco "q$_0$" (=E$_{had,vis}$)**
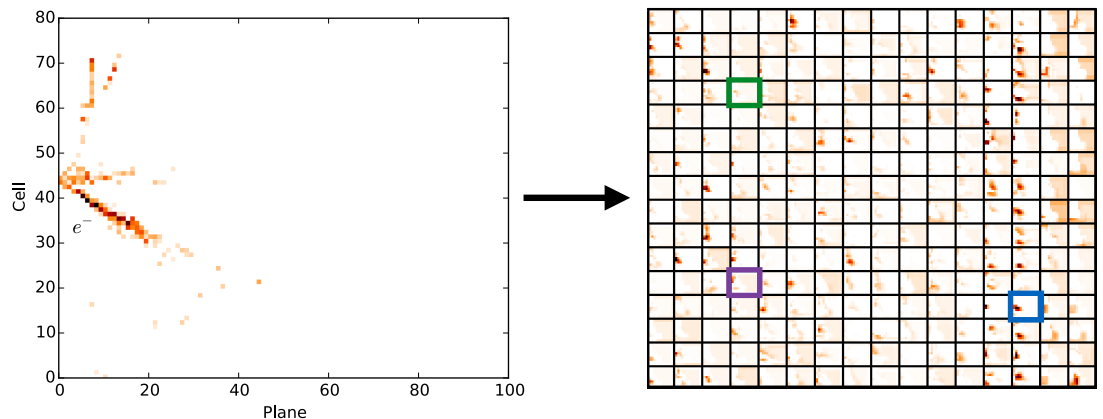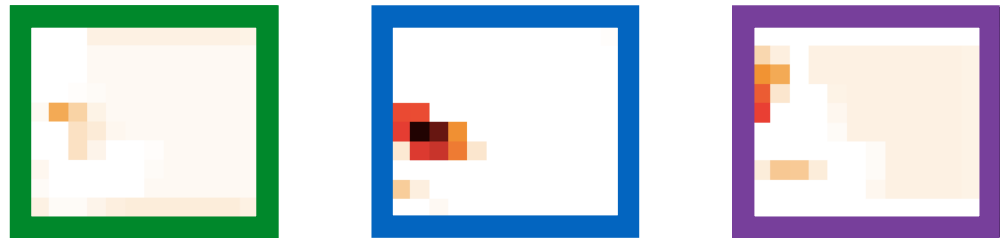
# Scattering in a Nuclear Environment

☐ Enable GENIE empirical Meson Exchange Current Model

☐ Reweight to match NOvA excess as a function of 3-momentum transfer

- 50% systematic uncertainty on MEC component

- Reduces largest systematics
  – hadronic energy scale
  – QE cross section modeling

- Reduce single non-resonant pion production by 50%

  (P.A. Rodrigues et al, arXiv:1601.01888.)

MEC model by S. Dytman, inspired by
J. W. Lightbody, J. S. O'Connell, Computers in Physics 2 (1988) 57.



$10^3$ Events

Reco "$q_0$" (=$E_{had,vis}$)

0.1 < |**q**|/GeV < 0.2

0.2 < |**q**|/GeV < 0.3

0.3 < |**q**|/GeV < 0.4

0.4 < |**q**|/GeV < 0.5

0.5 < |**q**|/GeV < 0.6
- NOvA ND Data
- MEC
- QE
- RES
- DIS
- Other

0.6 < |**q**|/GeV < 0.7

0.7 < |**q**|/GeV < 0.8

0.8 < |**q**|/GeV < 0.9

0.9 < |**q**|/GeV < 1

# Improved Event Selection

- This analysis features a new event selection technique based on ideas from computer vision and deep learning

  □ Calibrated hit maps are inputs to Convolutional Visual Network (CVN)

  □ Series of image processing transformations applied to extract abstract features

  □ Extracted features used as inputs to a conventional neural network to classify the event
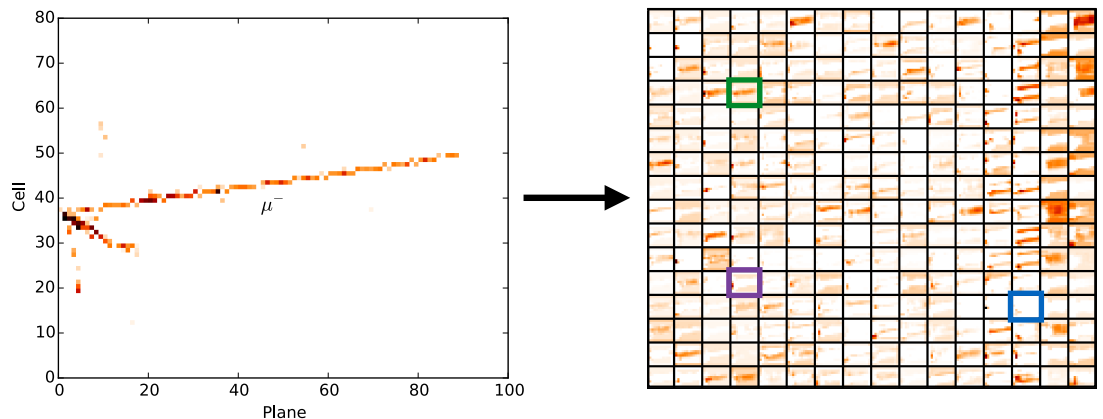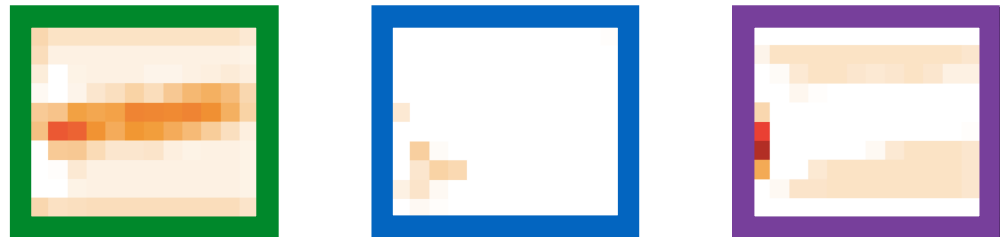


A. Aurisano et al., arXiv:1604.01444

Posters P1.028 by A. Radovic, P1.032 by F. Psihas and A. Himmel for more detail

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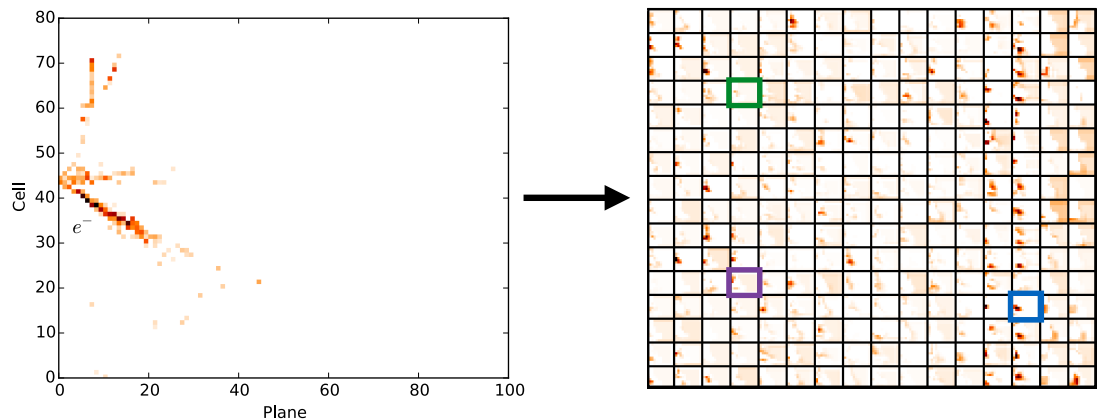
A. Aurisano et al., arXiv:1604.01444

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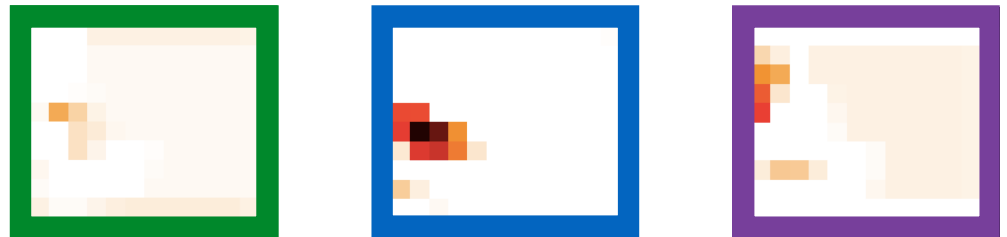


Improvement in sensitivity from CVN equivalent to 30% more exposure