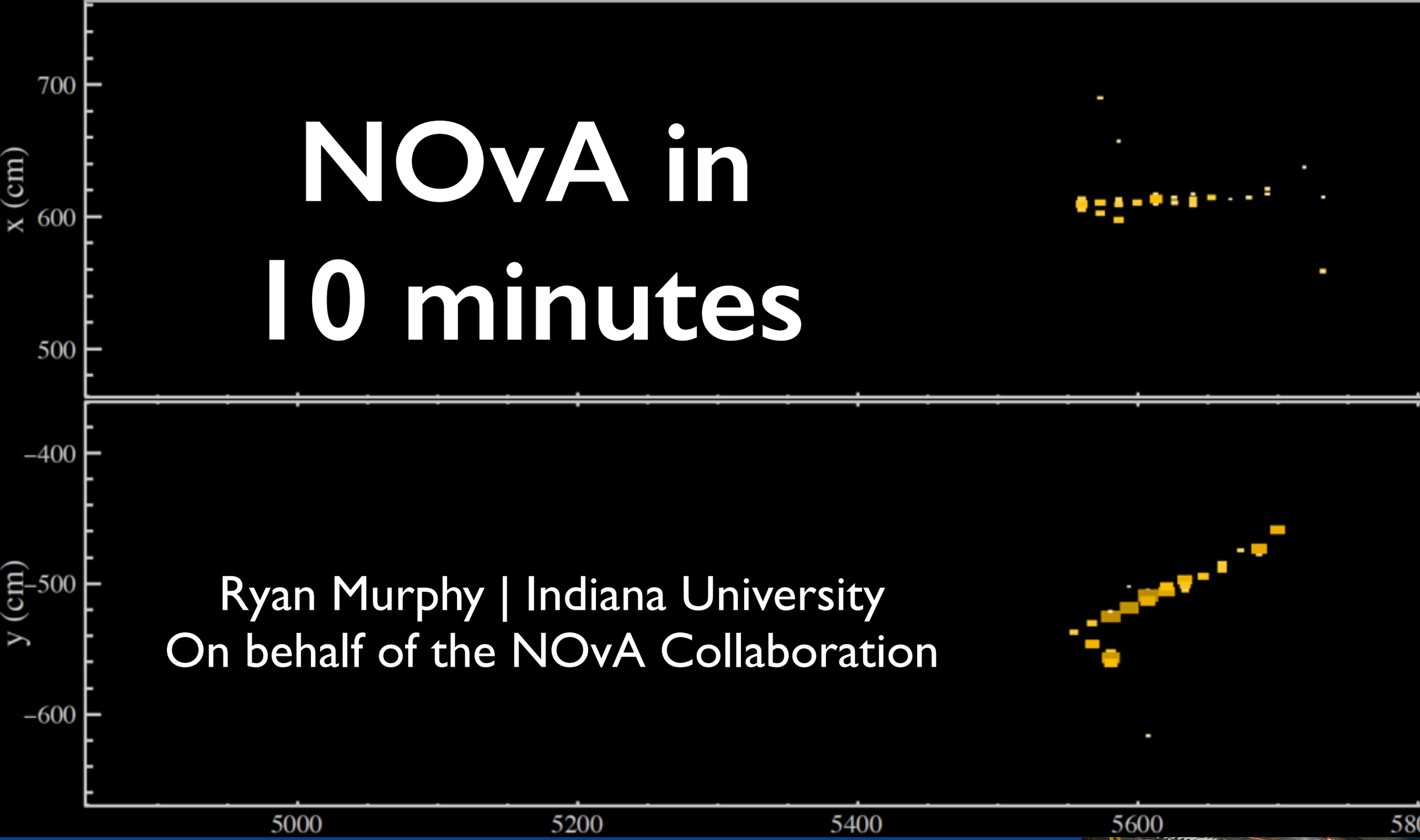
NOvA in 10 minutes

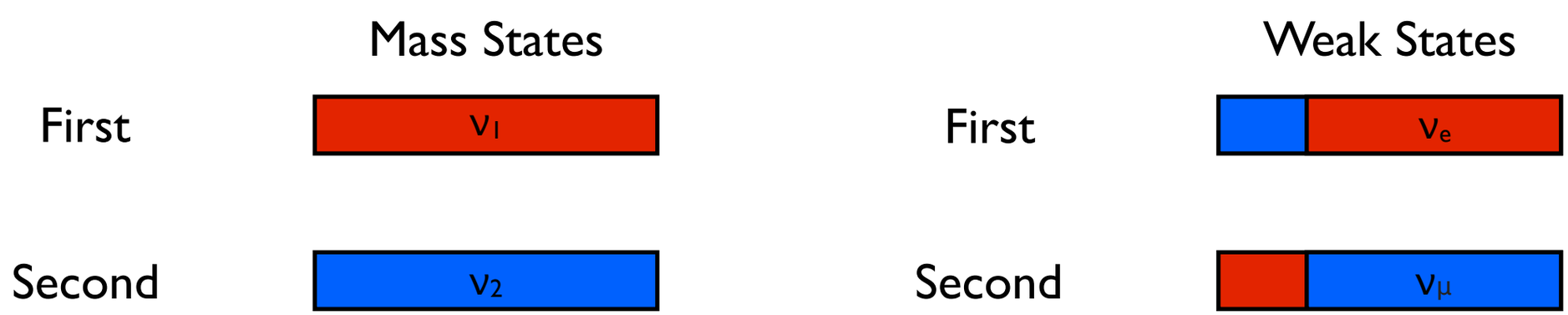
Ryan Murphy | Indiana University
On behalf of the NOvA Collaboration



Fermilab | New Perspectives 2017
June 06, 2017

Neutrino Oscillations

- Neutrinos experimentally shown to oscillate, proving they have mass. 2015 Nobel Prize in Physics!
- Mass states are made up of a linear superposition of weak states.
- Two Neutrino Example:

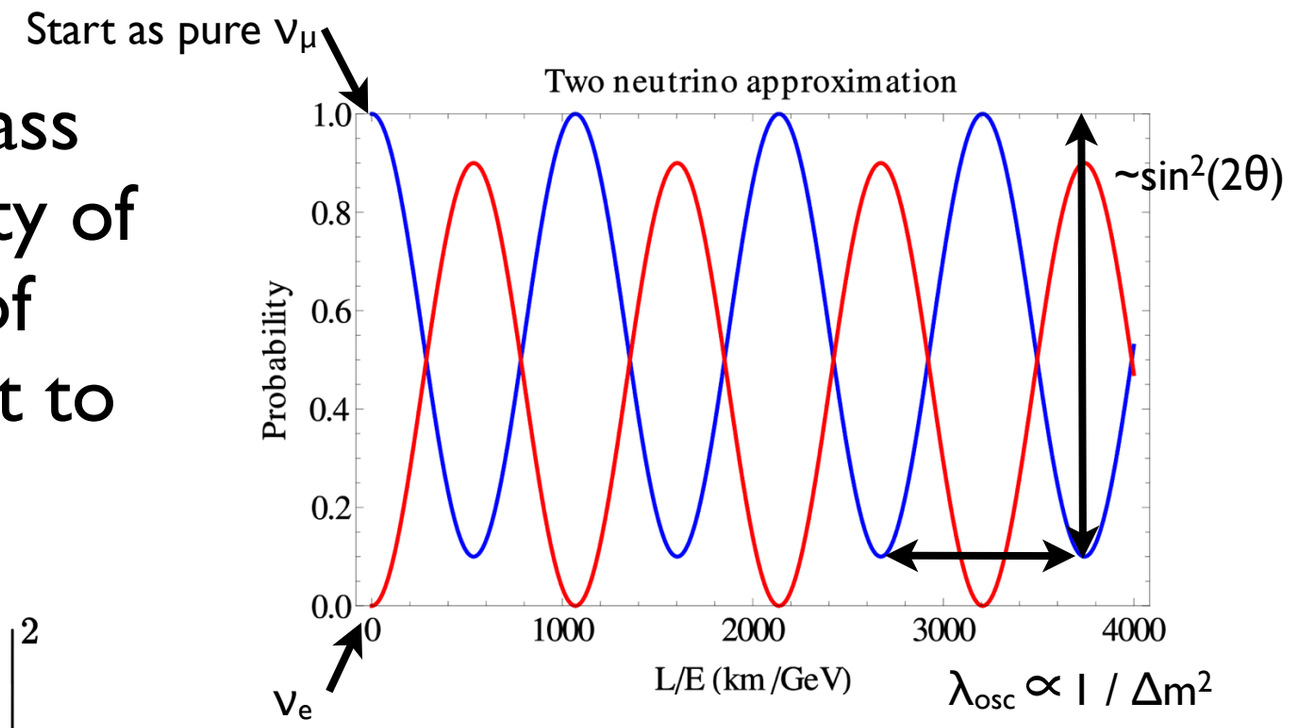


$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Mixing Matrix

Neutrino Oscillations

Constructive interference of mass components causes the probability of measuring a particular flavor of neutrino to oscillate with respect to distance/energy



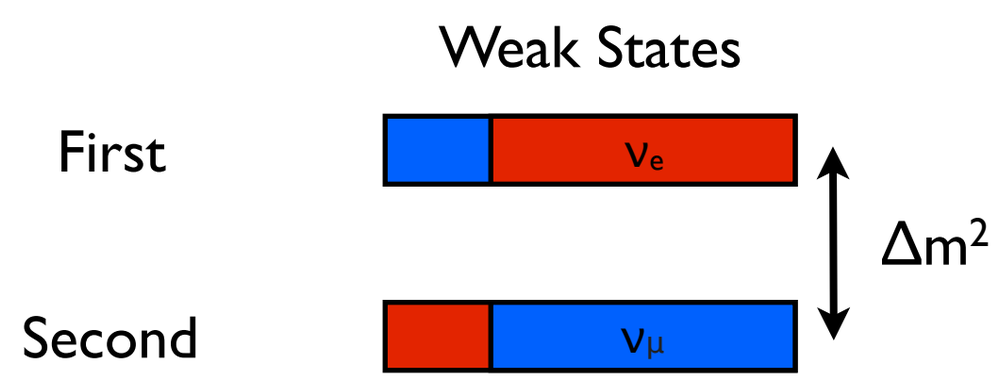
$$P_{\alpha\to\beta} = |\langle \nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/2E}\right|^2$$

Appearance

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

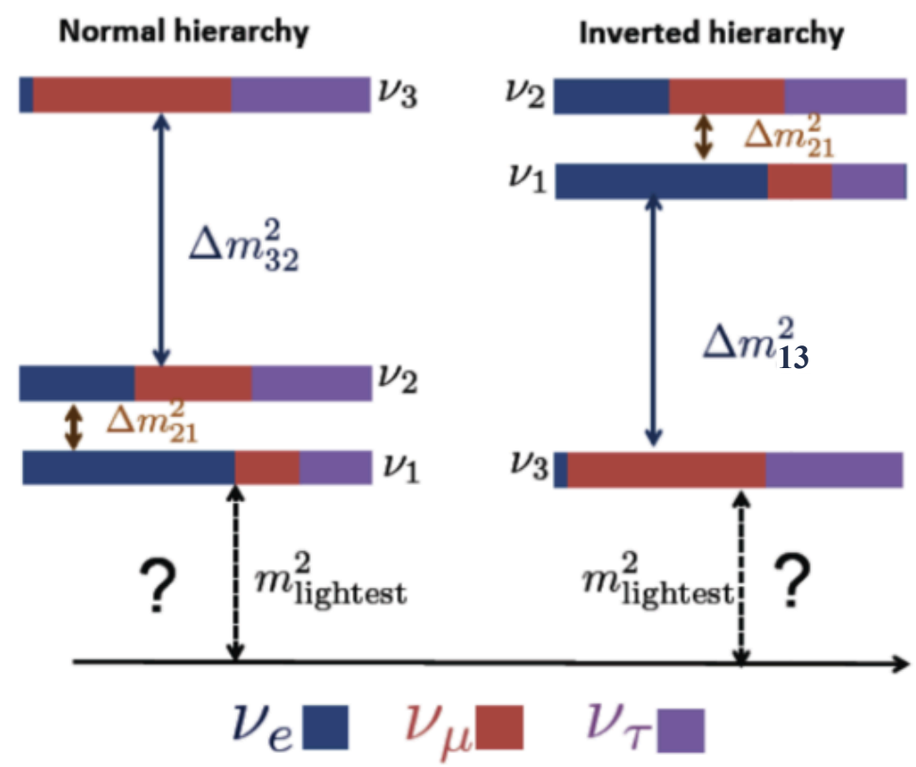
Disappearance

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



Questions in Neutrino Physics

- Normal or Inverted Hierarchy?
- What, are the values of θ_{12}, θ_{13}, θ_{23}, and δ_{CP} ?
- What are the masses of neutrinos?
- Are there more than 3 flavors of neutrinos?
- Is the neutrino its own antiparticle?



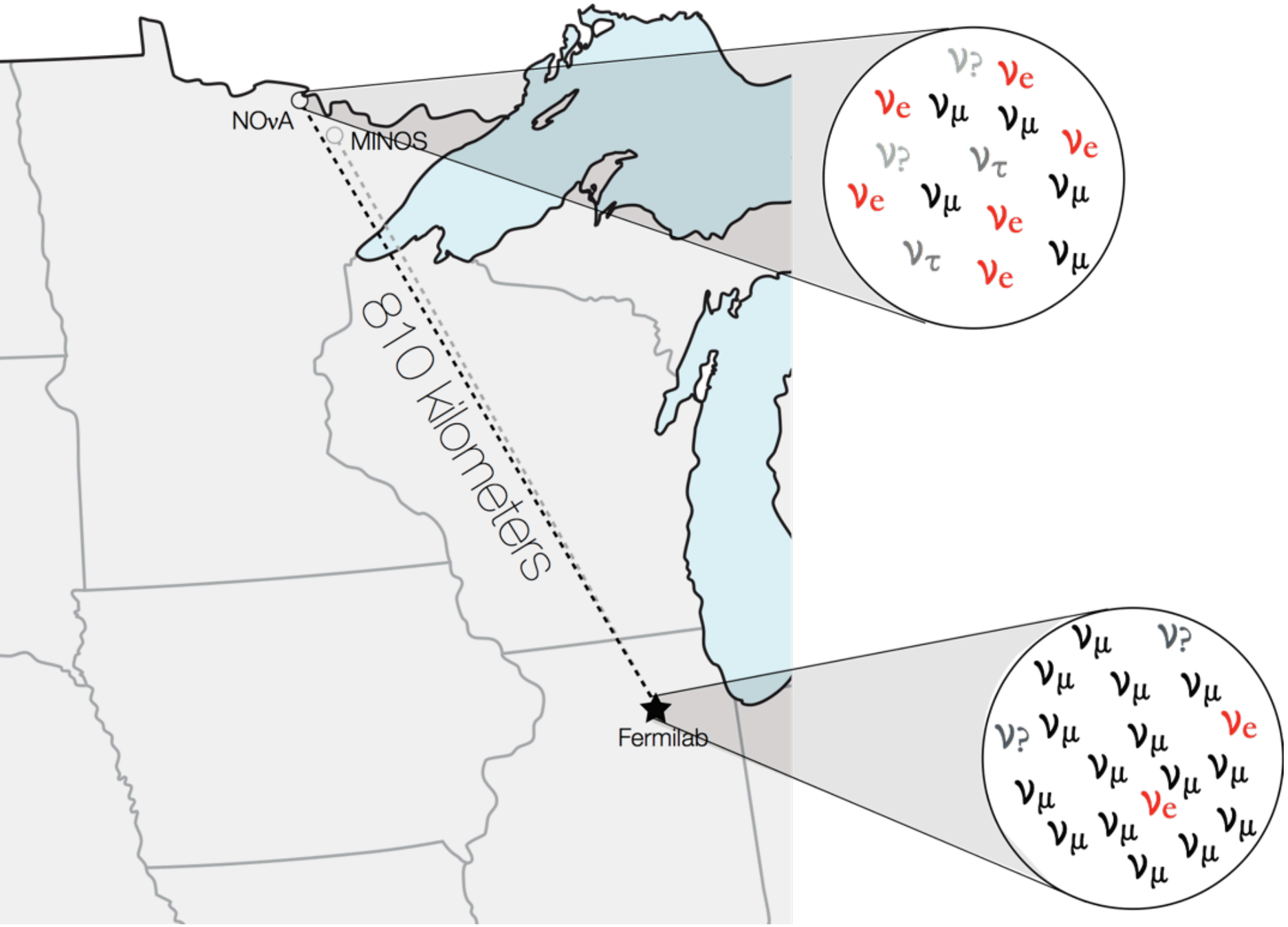
PMNS Mixing Matrix

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$s_{ij} = \sin\theta_{ij}$ $\qquad$ $c_{ij} = \cos\theta_{ij}$

NOvA Overview

NuMI **O**ff-axis ν_e **A**ppearance



- NOvA is a long-baseline neutrino oscillation experiment
- Observes neutrinos from NuMI beamline at Fermilab
- Two functionally identical detectors, situated 14 mrad off axis, 810 km apart
- Near Detector is 300 tons, located at FNAL
- Far Detector is 14 ktons, located in Ash River, MN

NOvA Physics Program

Disappearance channel ($\nu_\mu \to \nu_\mu$ & $\bar{\nu}_\mu \to \bar{\nu}_\mu$)

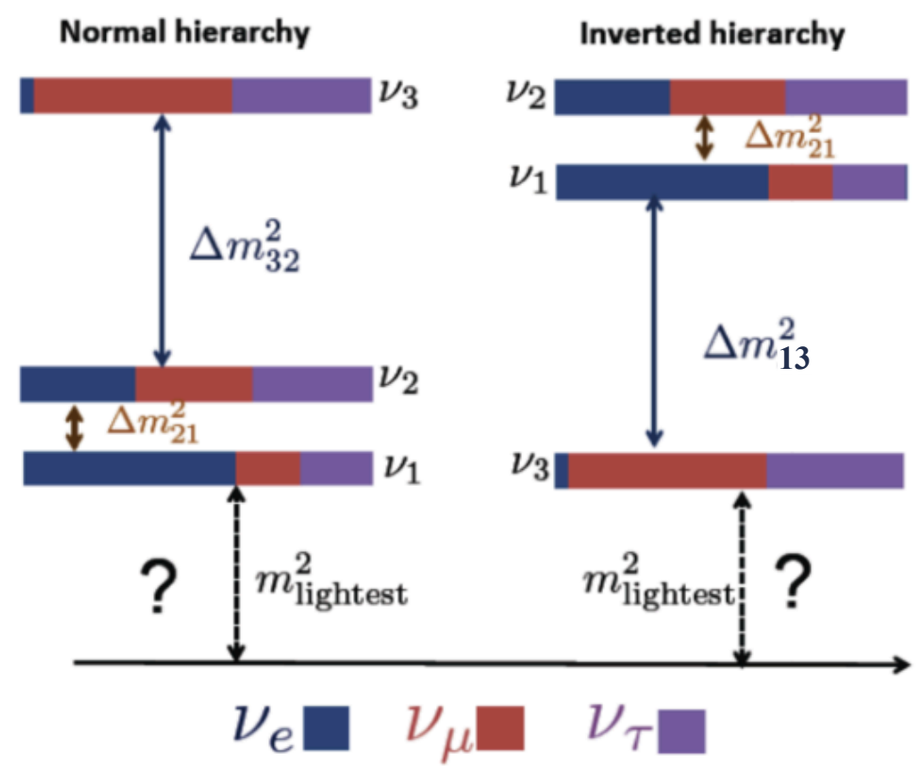
- Measurements of $\sin^2(\theta_{23})$ and Δm^2_{32}

Appearance channel ($\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$)

- Determine ν mass hierarchy
- Octant of θ_{23} (> or < 45°)
- Constrain δ_{CP}

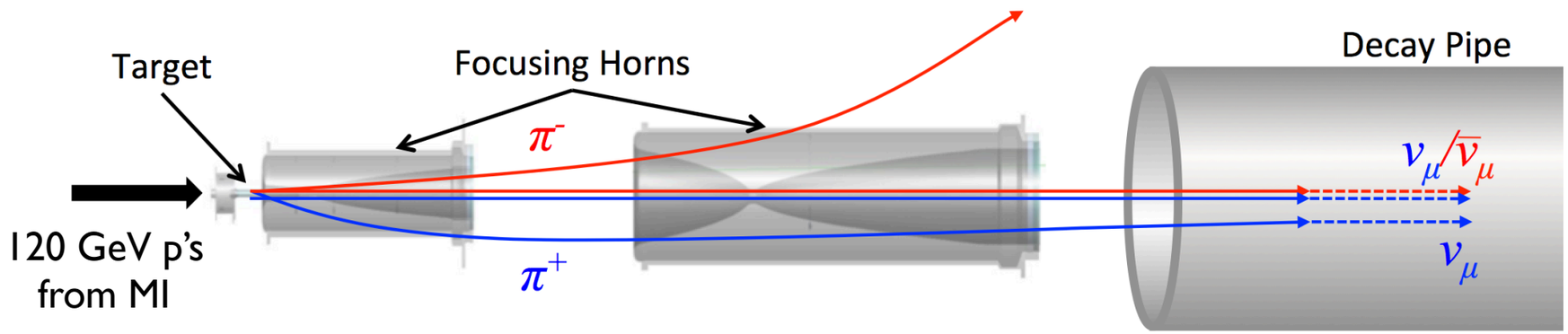
Bonus Physics

- Cross sections with NOvA ND
- Supernova neutrinos
- Sterile Neutrino Search
- Plus more!

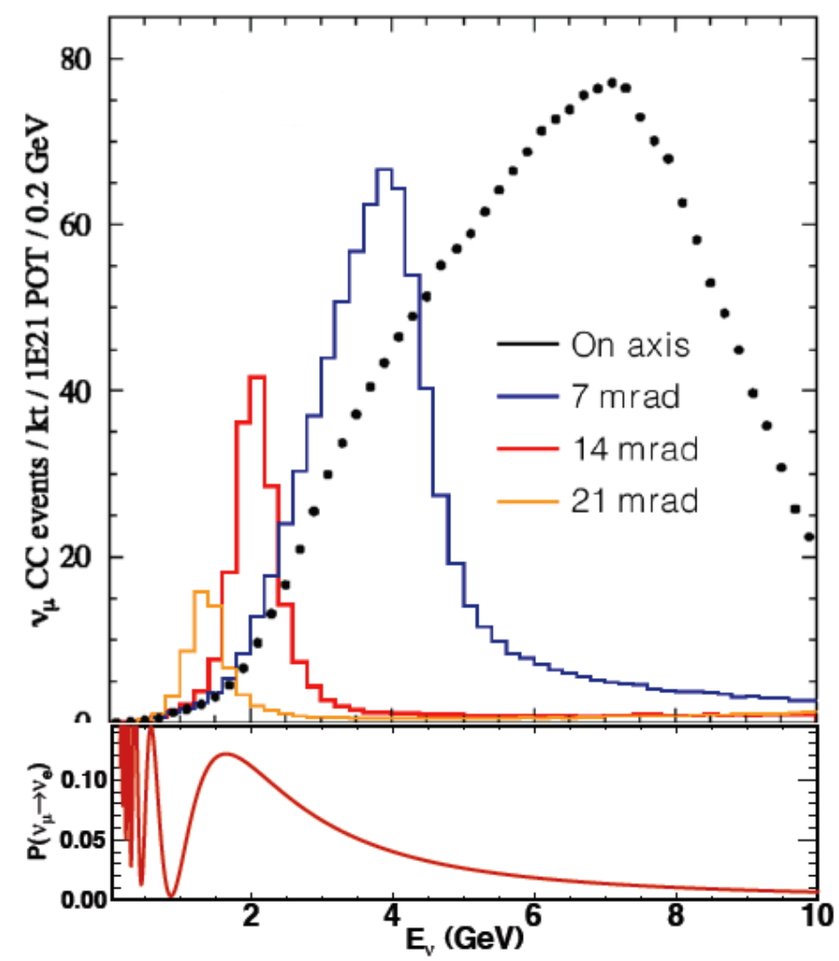


NuMI Beam

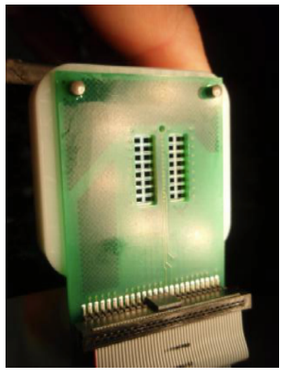
Neutrinos (νs) at the **M**ain **I**njector



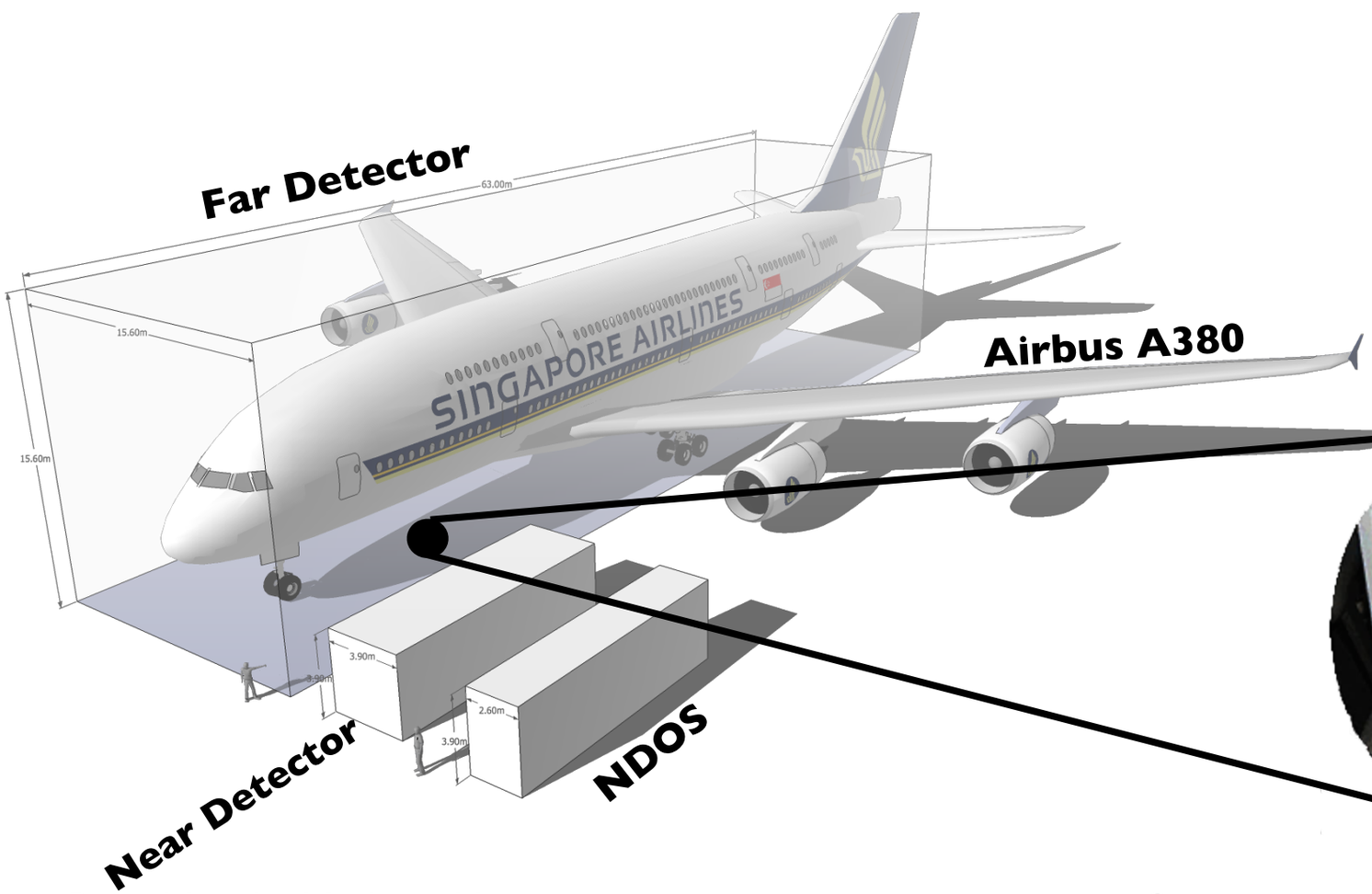
- Most powerful neutrino beam in the world at **700 kW**!
- 120 GeV protons from MI hit a target to produce charged kaons and pions
- Magnetic horn focuses charged particles, selects sign
- $K^+, \pi^+ \rightarrow \mu^+ + \nu_\mu$ to create a neutrino beam
- Beam pulses for 10μs every 1.33 seconds
- Sitting 14 mrad off axis provides NOvA with a narrow band beam peaked at ~2 GeV, optimal for observing the **appearance** channel

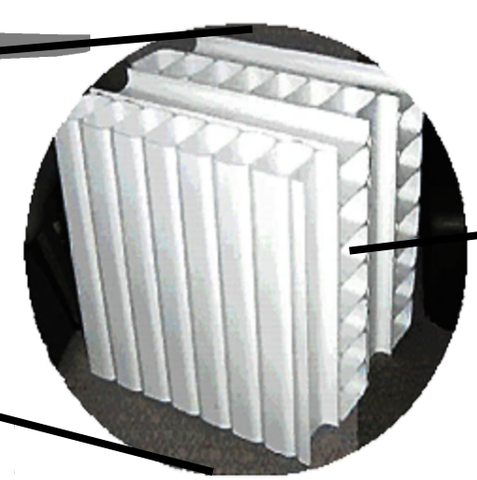


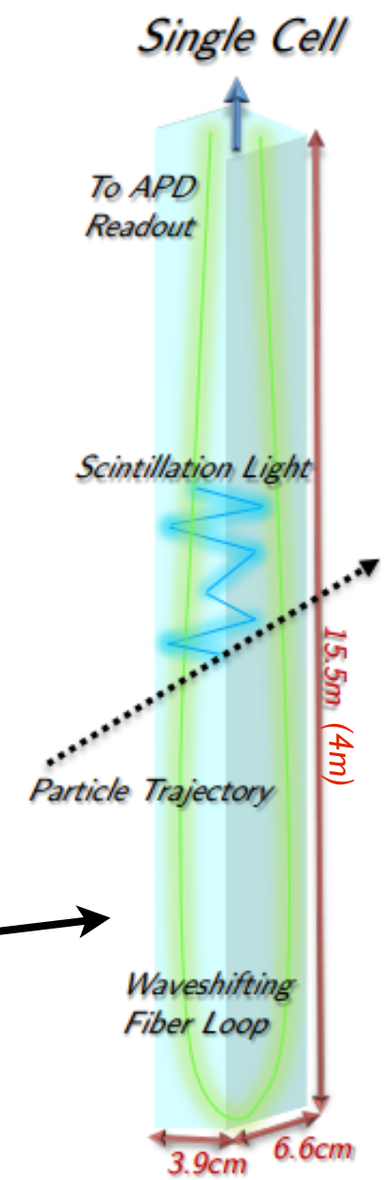
NOvA Detectors



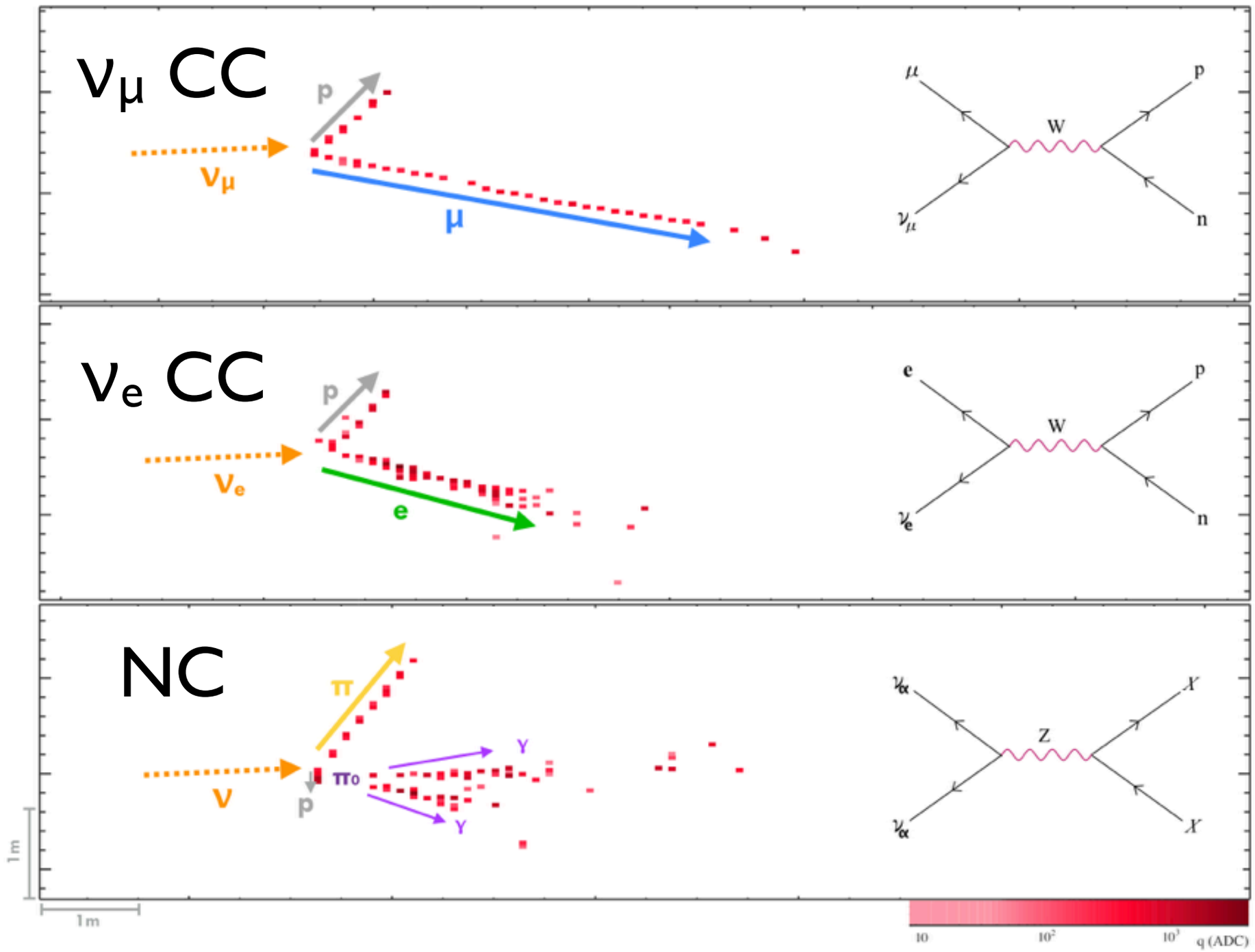
- Cells are made of reflective PVC material
- Cells are filled with liquid scintillator
- 0.7mm wavelength shifting fiber is read out to a Avalanche Photo Diode (APD)
- Planes are layered orthogonally to provide **3D particle tracking**
- Far Detector has **~344k channels**
- Near Detector has ~20k channels







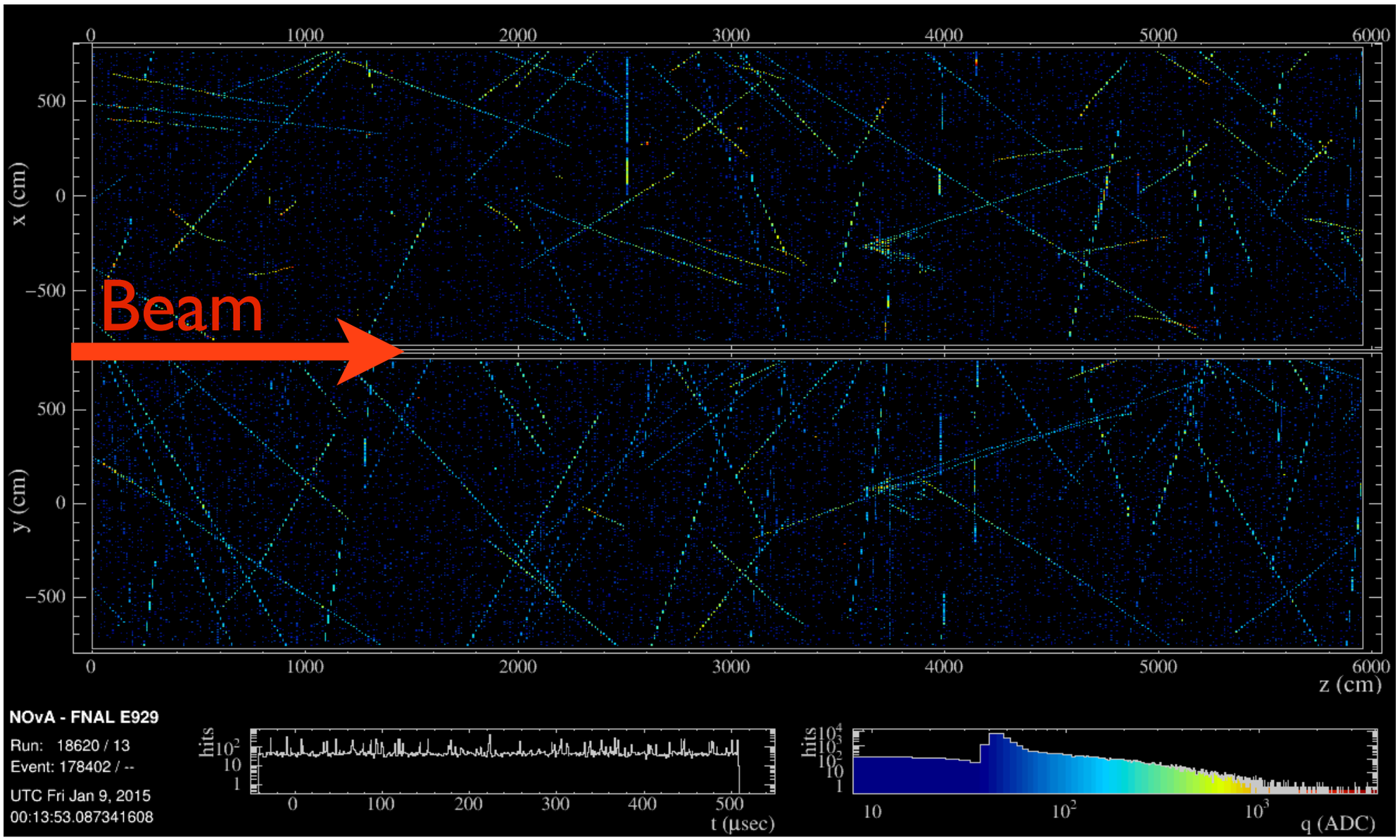
Neutrino Topology



Finding Neutrino Events in the FD

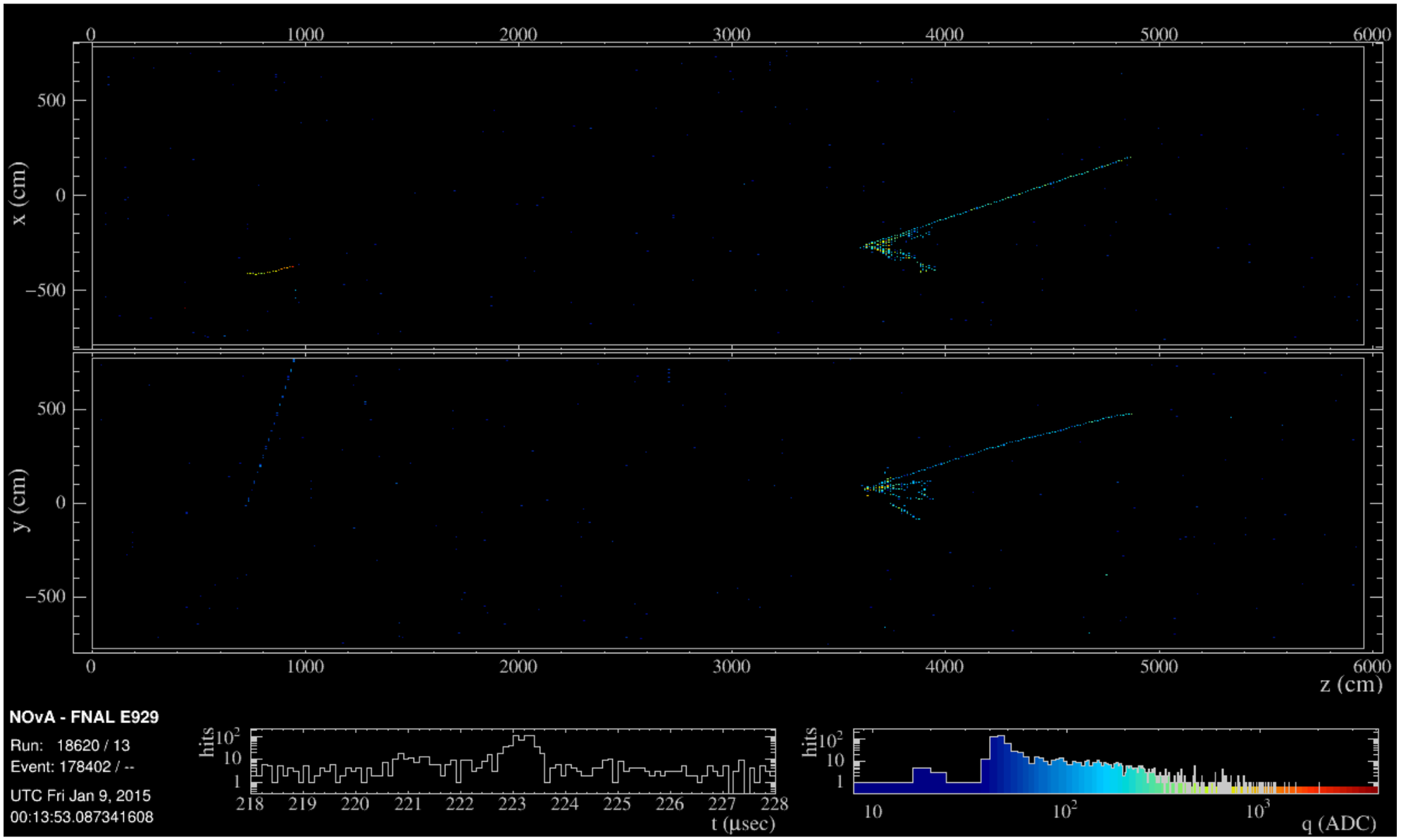
Top

Side



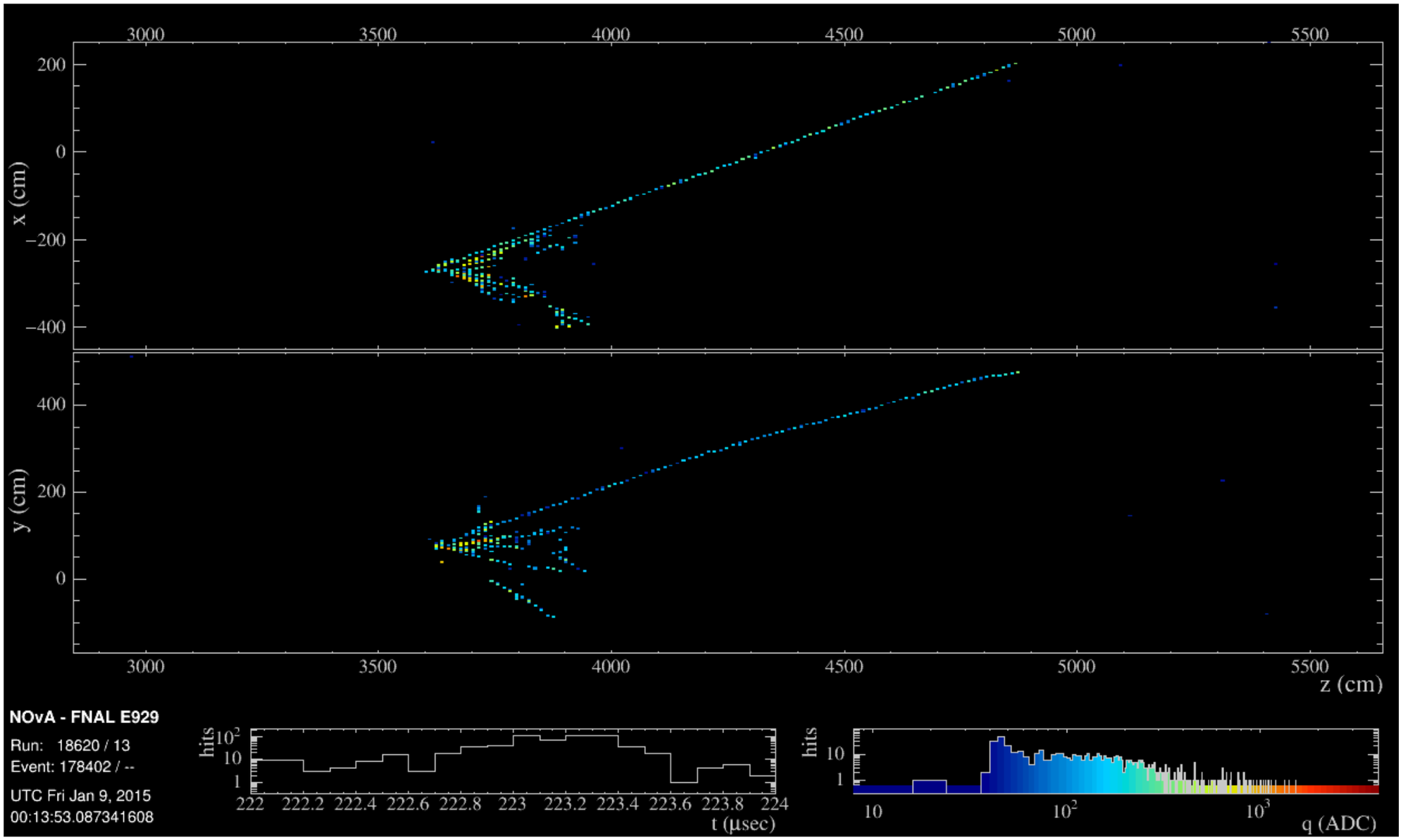
A 550μs exposure of the Far Detector is recorded

Finding Neutrino Events in the FD



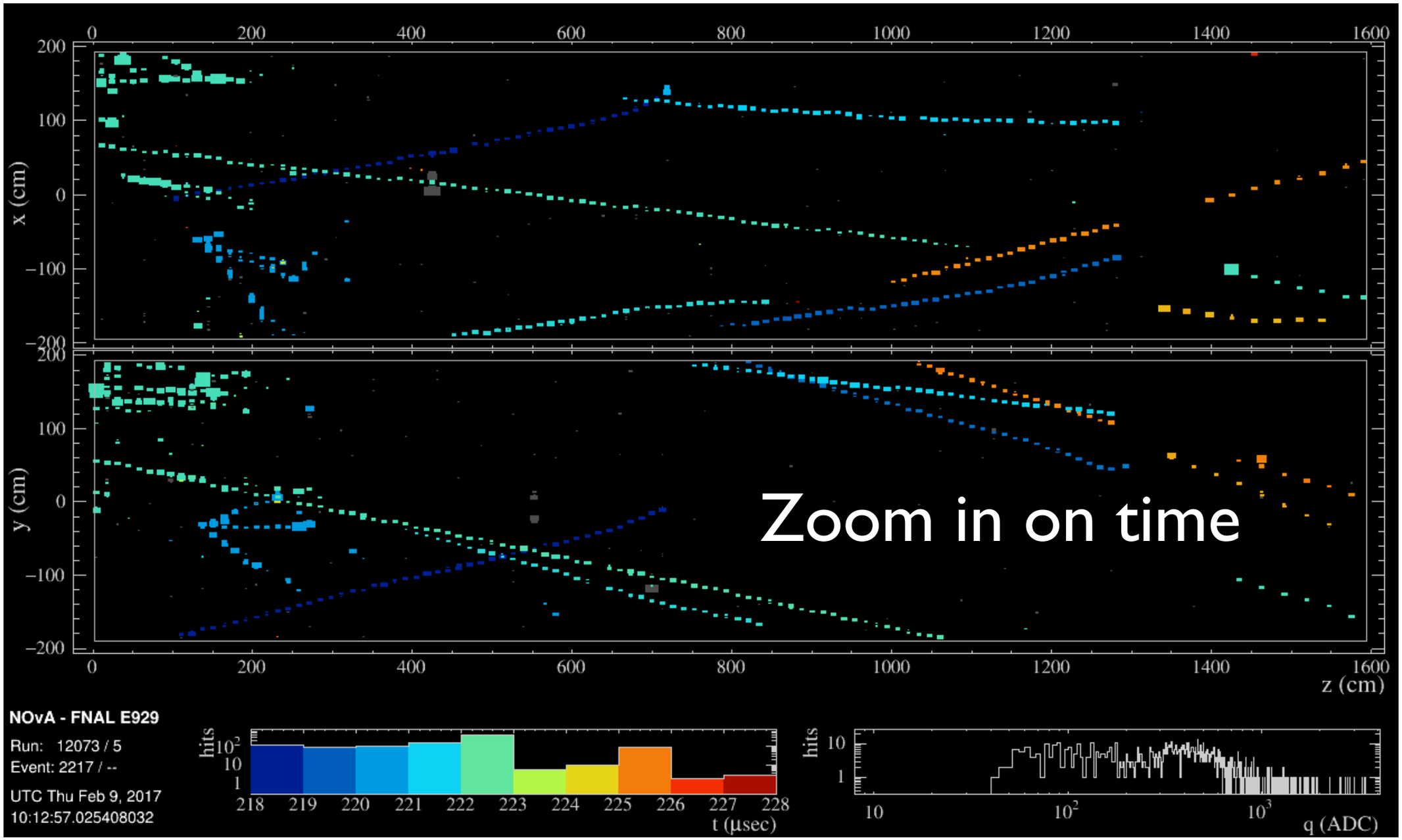
Zoom in on the 10μs of beam spill

Finding Neutrino Events in the FD

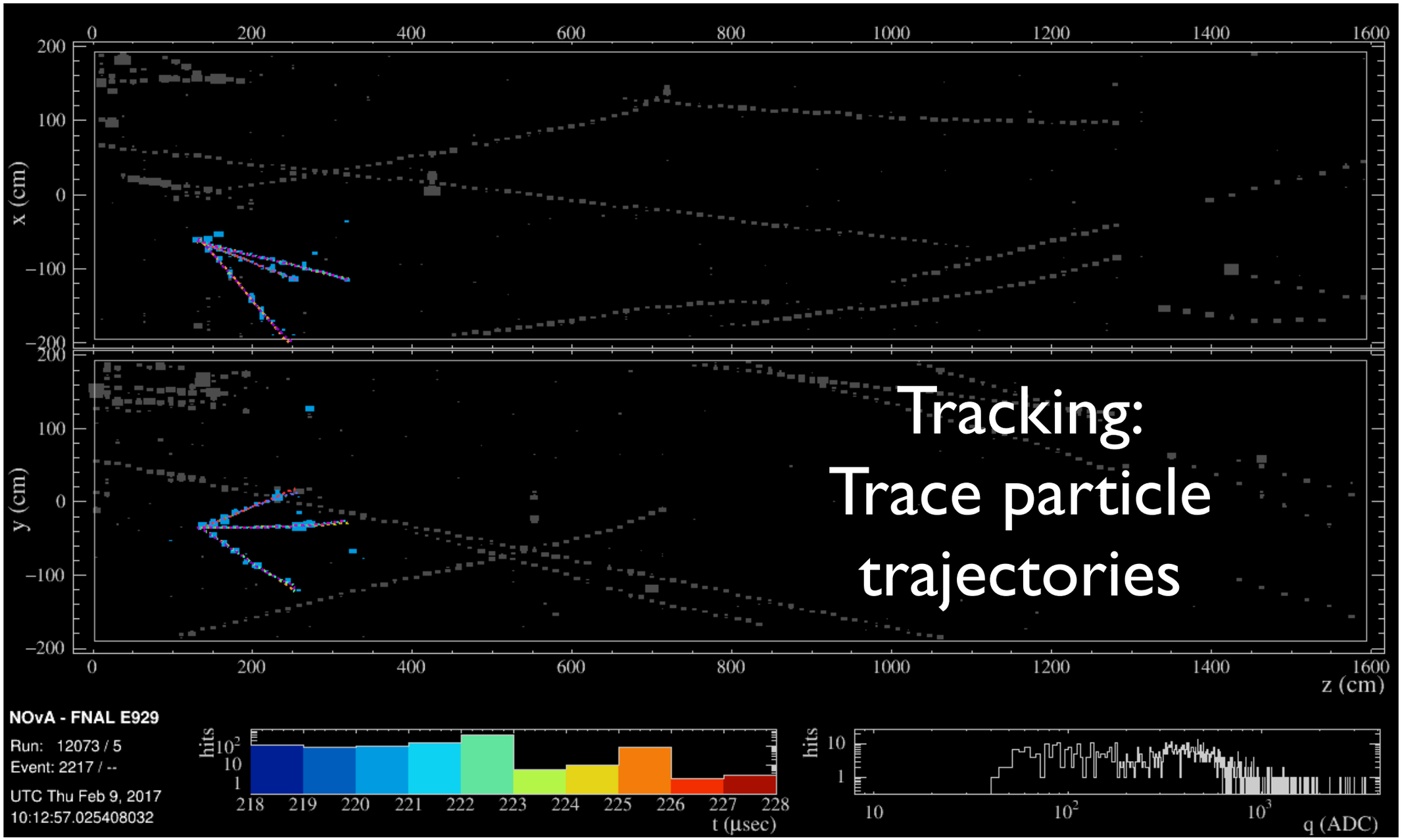


Zoom in spatially on neutrino candidate

Reconstruction of Neutrino Events in ND

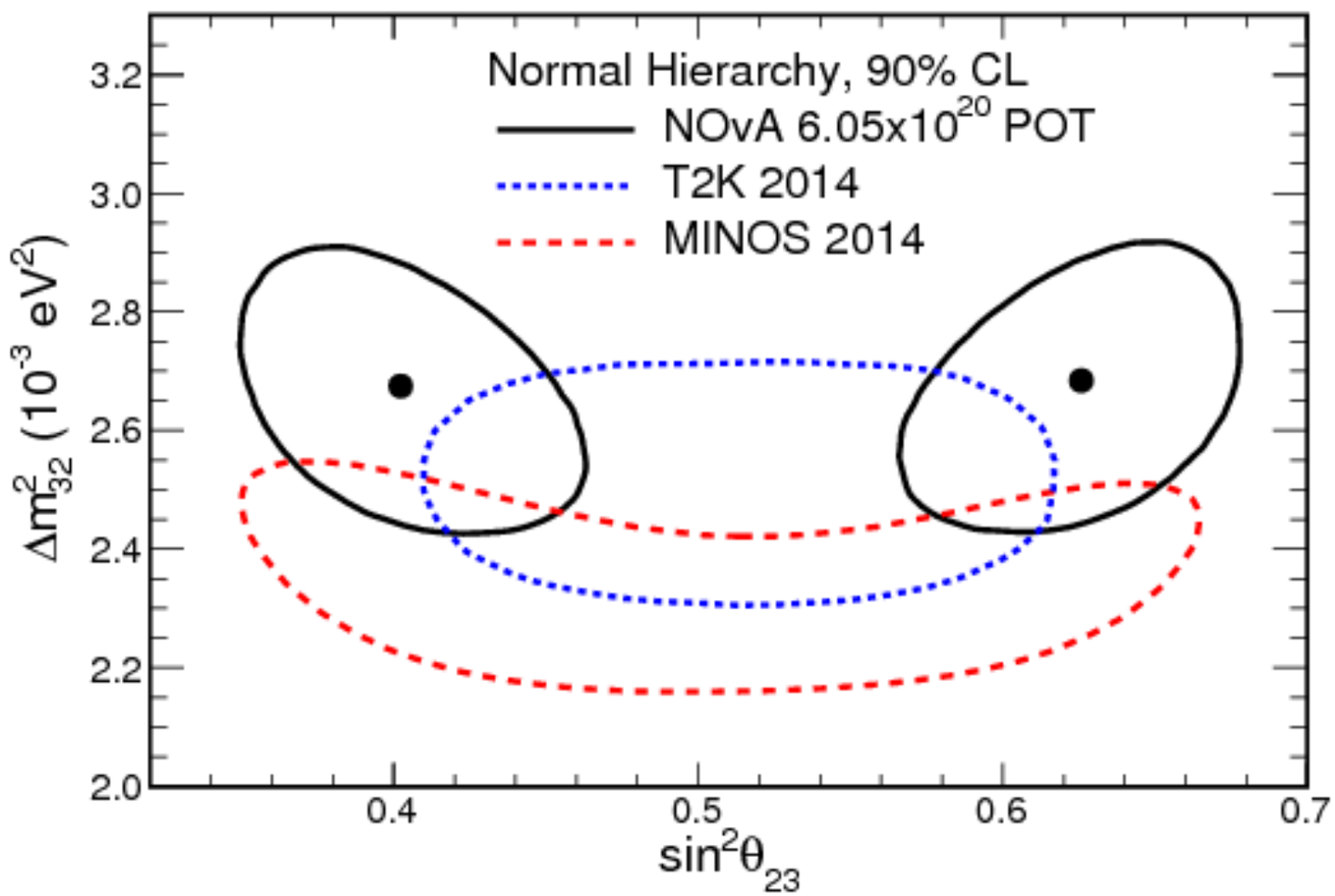


Reconstruction of Neutrino Events in ND



Tracking:
Trace particle trajectories

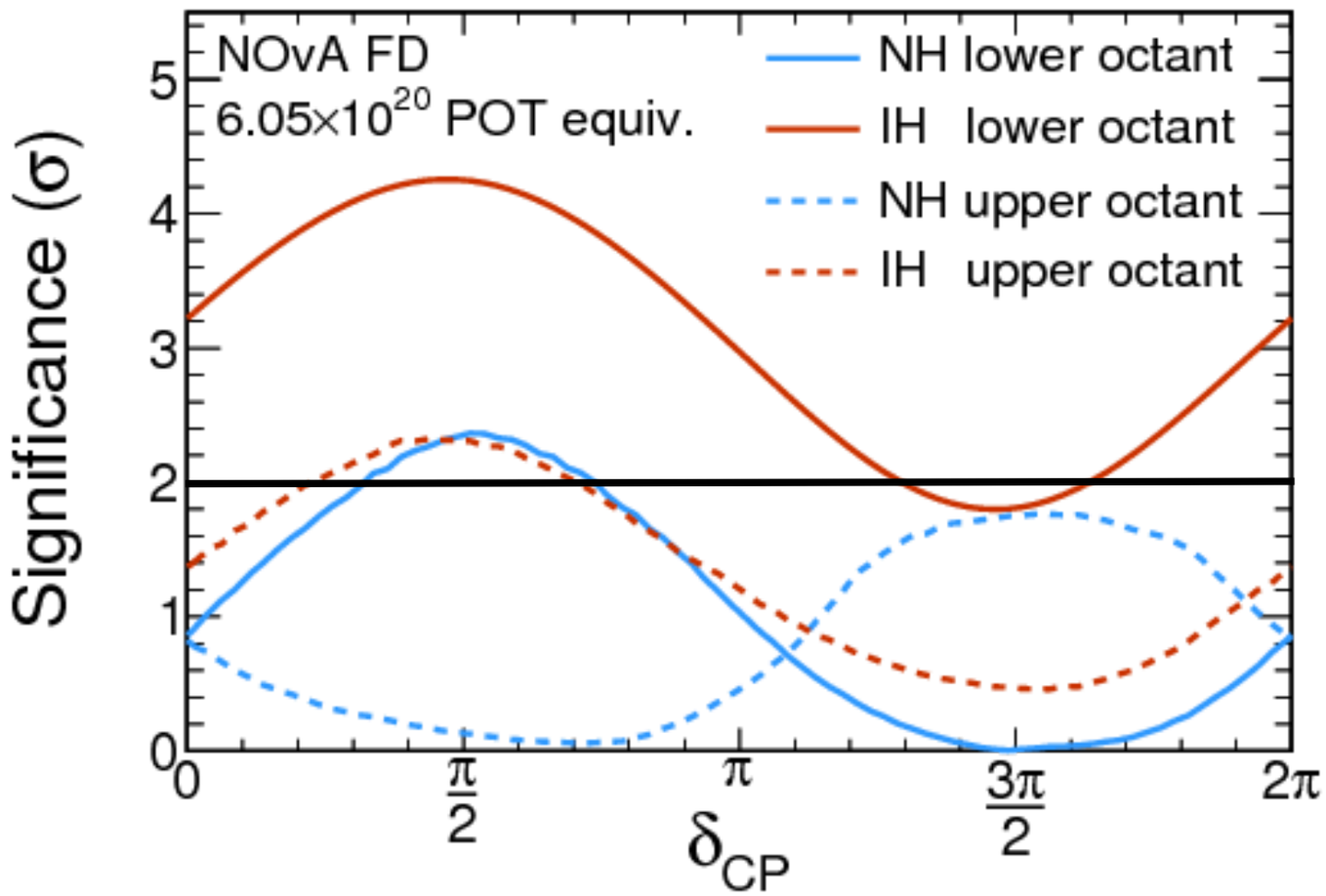
Measurement of the neutrino mixing angle θ_{23} in NOvA



- PhysRevLett.118.151802
- $\Delta m^2_{32} = (2.67 \pm 0.11)\times 10^{-3}\ eV^2$
- Maximal mixing disfavored at 2.6σ

- 2 degenerate best fit points in Normal Hierarchy
  $\sin^2(\theta_{23}) = 0.404$
  $\sin^2(\theta_{23}) = 0.623$

Constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in NOvA



- PhysRevLett.118.231801 (Just published!)
- Inverted Hierarchy in lower octant disfavored at ~2σ
- 2 degenerate best fit points in Normal Hierarchy
  $\sin^2(\theta_{23}) = 0.404$, $\boldsymbol{\delta_{CP} = 1.48\pi}$
  $\sin^2(\theta_{23}) = 0.623$, $\boldsymbol{\delta_{CP} = 0.74\pi}$

NOvA @ NP 2017

Day 2

"Data Monitoring and Performance of the NOvA Detectors" - **Teresa Lackey**

"Increased Neutrino Yield with the new NOvA Target Design: Simulation Study" - **Daisy Kalra**

"Calorimetric Energy Scale in the NOvA Detectors" - **Tyler Alion**

"Decomposition Methods for the ν_e Appearance analysis in the NOvA Near Detector" - **Nitish Nayak**

"Exploring the ν_μ charged-current uncontained sample at the NOvA Far Detector" - **Jose Sepulveda-Quiroz**

"Results From the Joint Fit to ν_e Appearance and ν_μ Disappearance in NOvA" - **Shiqi Yu**

"Sterile neutrino search in the NOvA Far Detector" - **Sijith Edayath**

NOvA @ User's Meeting 2017

"NOvA" - **Kanika Sachdev**

"The Physics Program of NOvA" (Poster) - **Alexander Radovic** and **Gavin Davies**

"Three-Flavor Oscillations in NOvA" (Poster) - **Erika Cantano-Mur** and **Kirk Bays**

"Sterile neutrino search through Neutral Current Disappearance in NOvA experiment" (Poster) - **Shaokai Yang** and **Sijith Edayath**

Summary

- NOvA is a world leading neutrino oscillation experiment
- Current analysis results provided important measurements (non maximal mixing!)
- Many more physics results to come!

www-nova.fnal.gov

Thank you!