Results from the NOvA Experiment

Erica Smith
Indiana University
for the NOvA Collaboration

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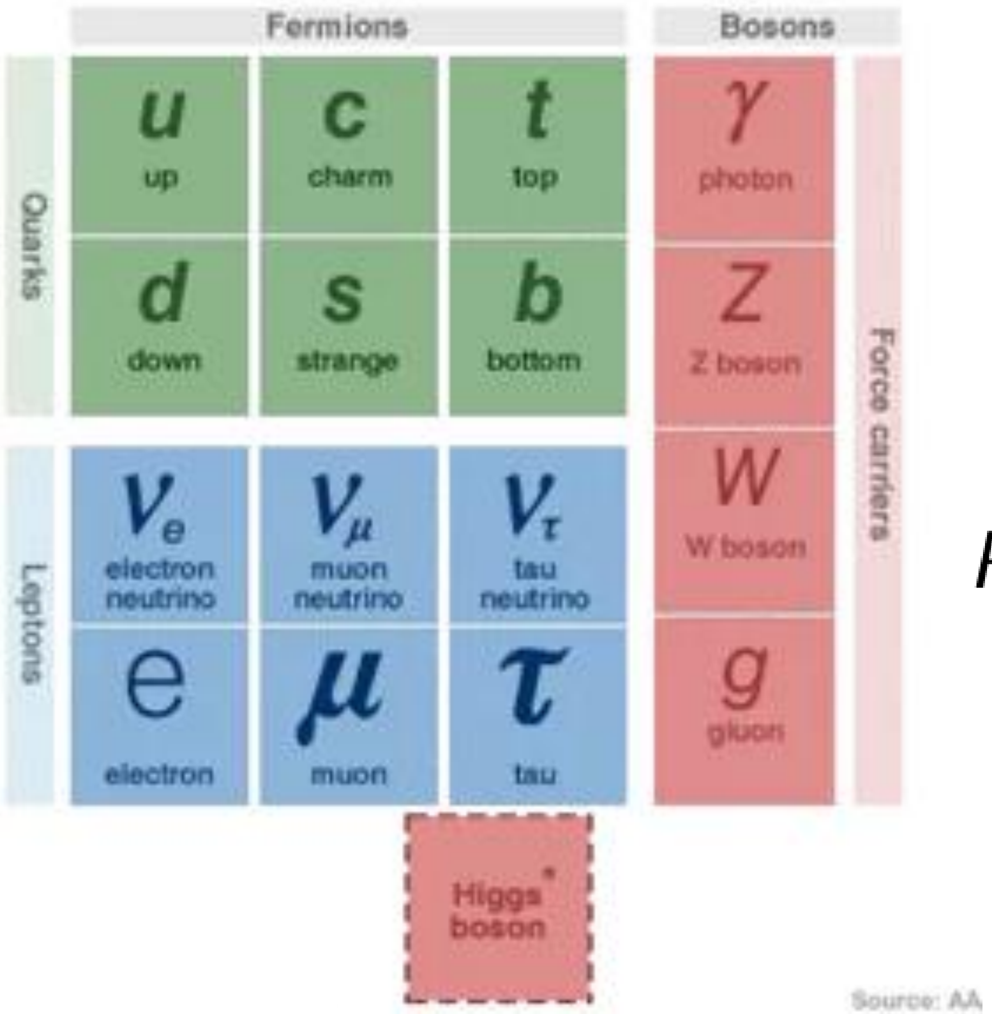
Neutrino Oscillations



Two Neutrino Case

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

Mass states

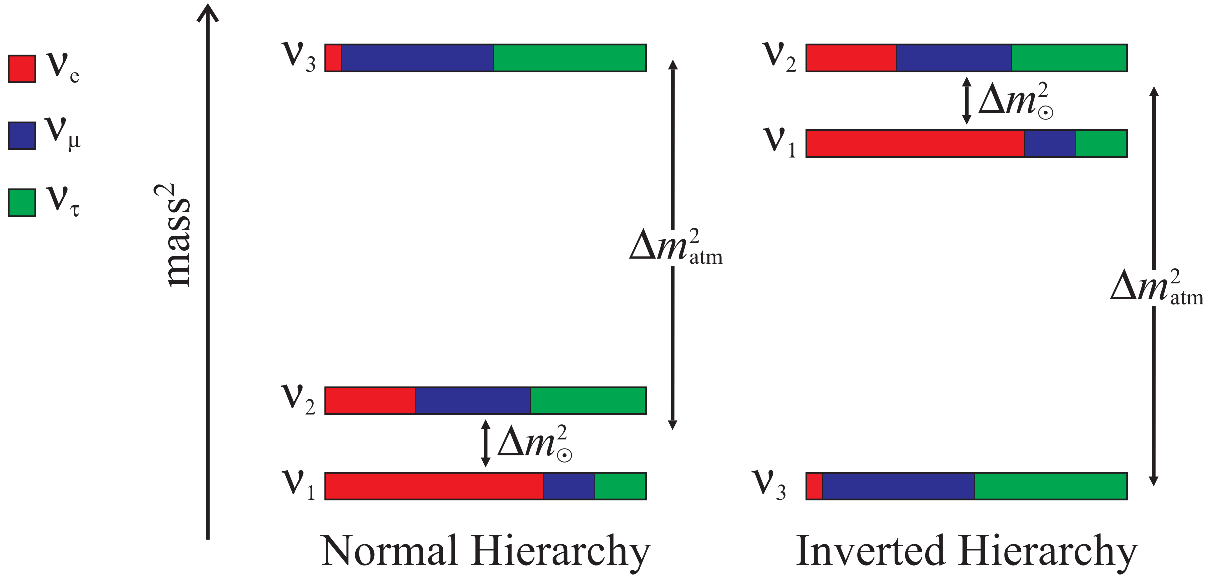
Flavor states

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

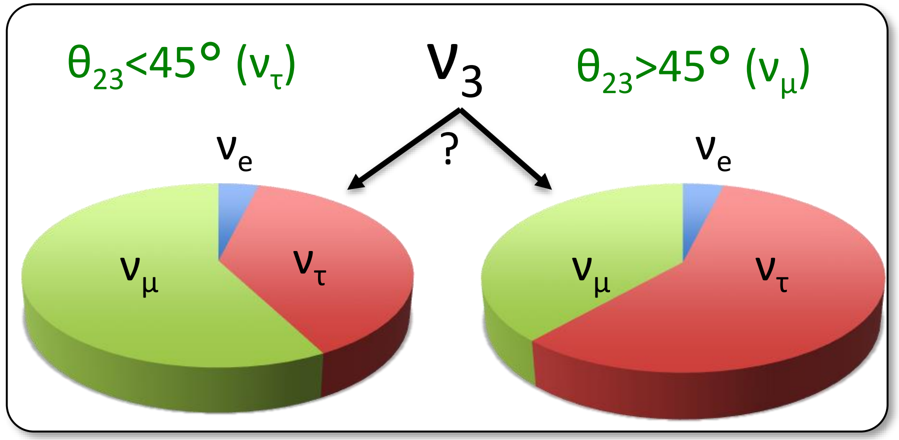
$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Unanswered Questions in Neutrino Physics

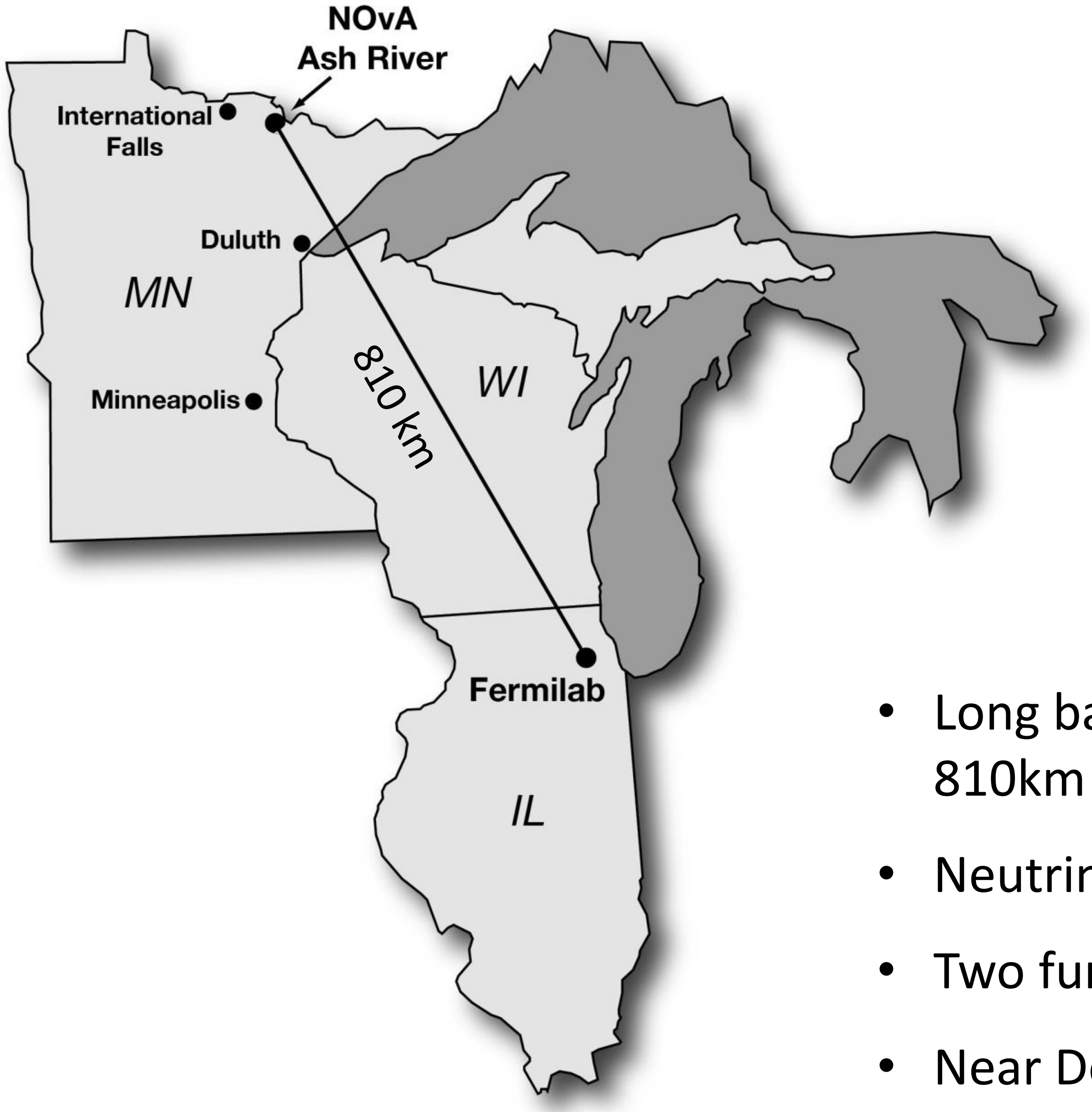
- Normal or Inverted hierarchy?
- Precision measurements of θ_{12}, θ_{13}, θ_{23}
- What is the octant of θ_{23}?
- Do neutrinos violate CP symmetry?
- Is there more to this story?

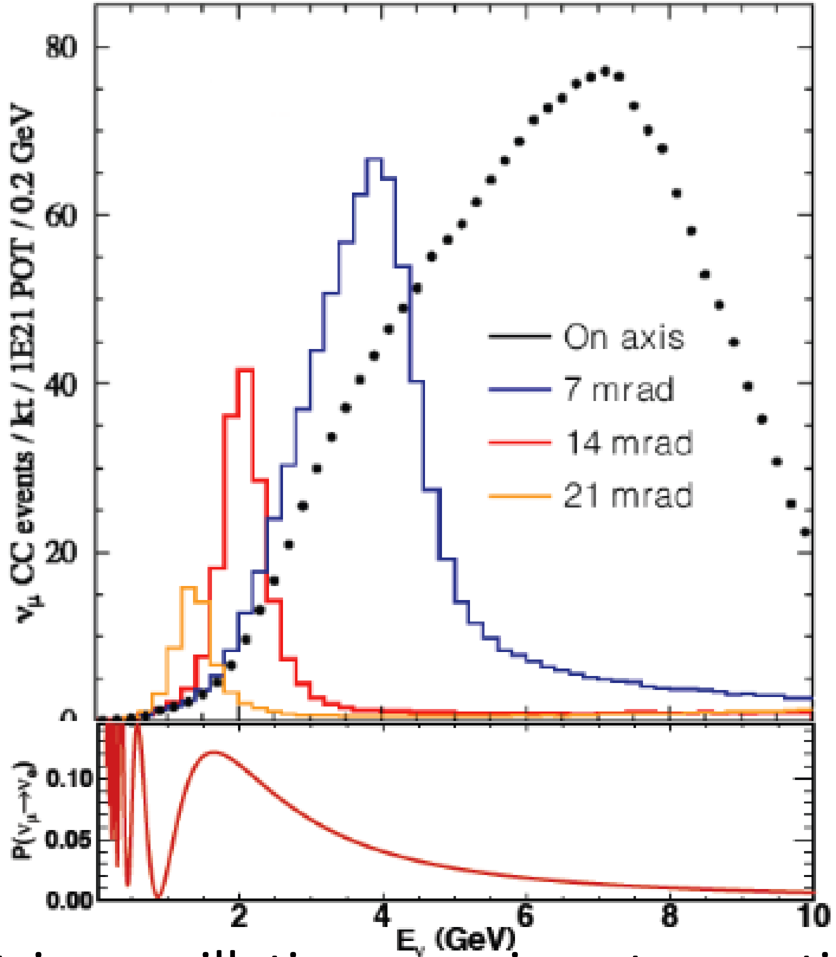


$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



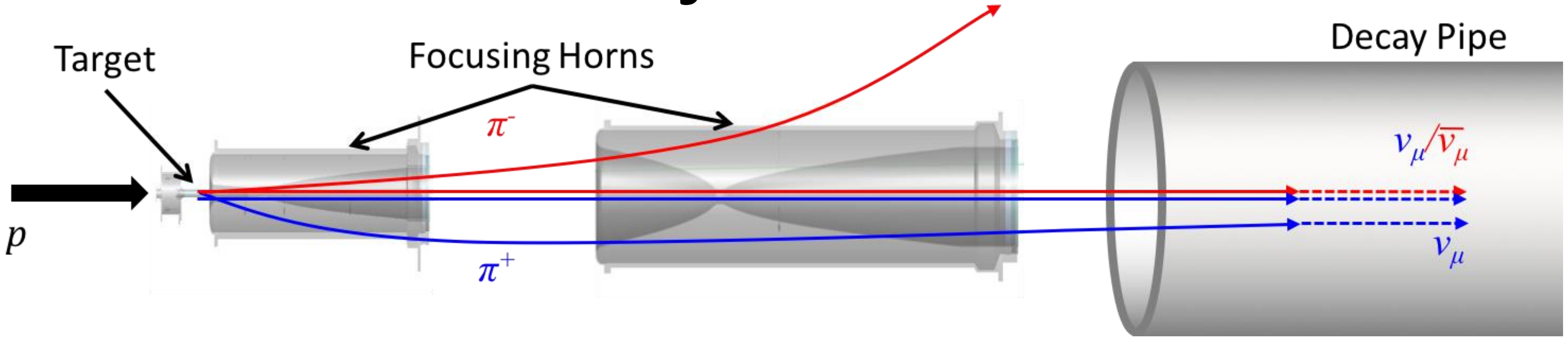
NuMI Off-Axis ν_e Appearance



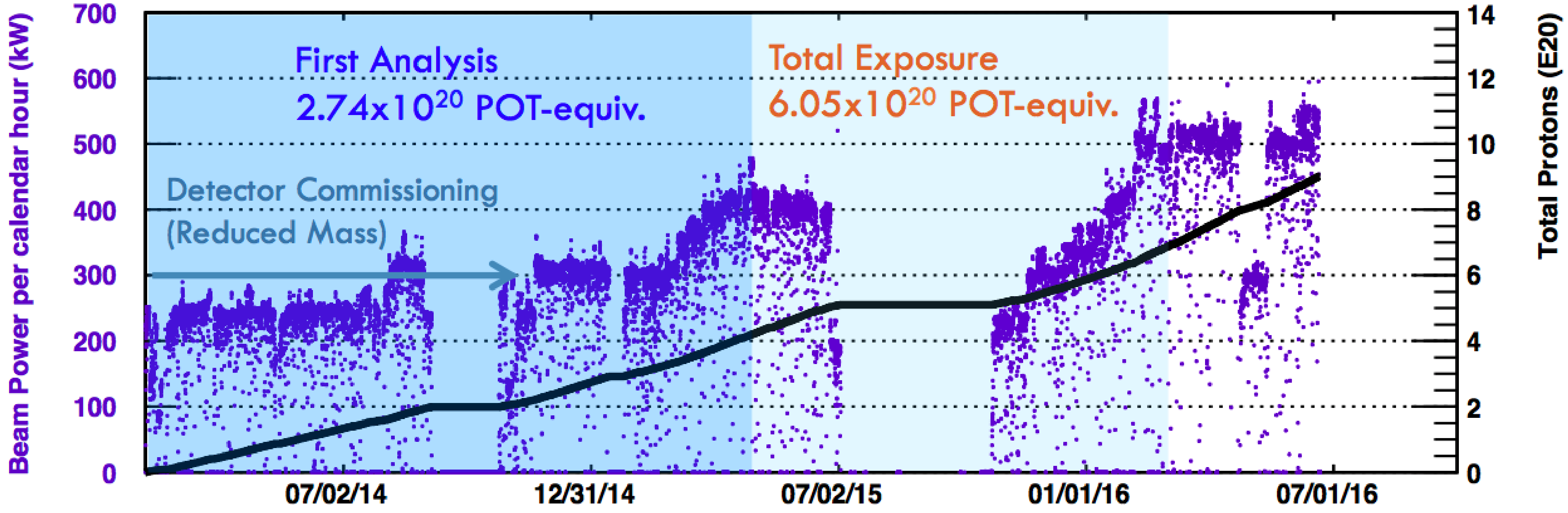


- Long baseline neutrino oscillation experiment operating at L/E = 810km / 2GeV
- Neutrinos from NuMI beam at Fermilab
- Two functionally identical detectors, 14.6mrad off beam axis
- Near Detector is 300 tons, at Fermilab, 100 m underground
- Far Detector is 14 ktons, located in Ash River, MN, on the surface

Neutrinos at the Main Injector



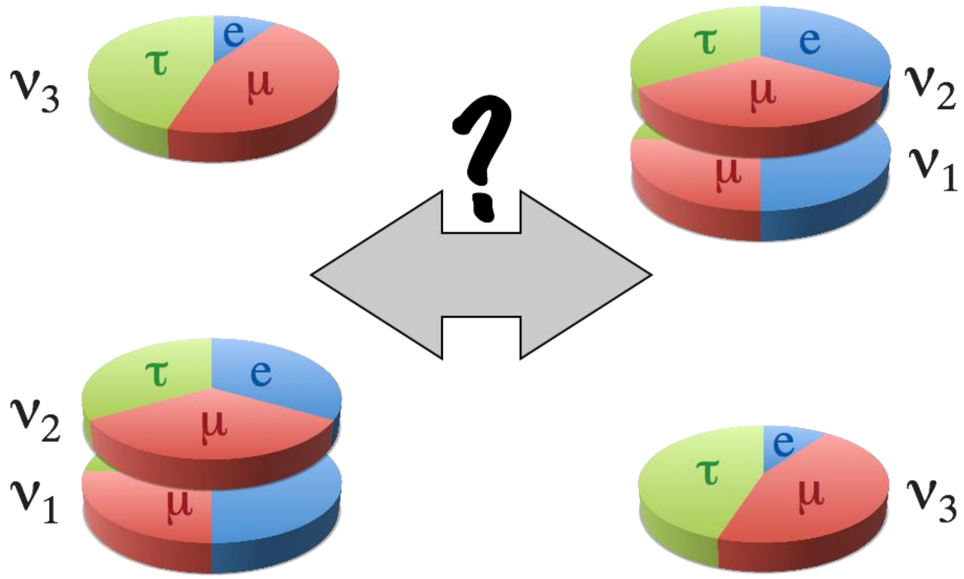
- 120 GeV protons from MI hit target to produce charged kaons and pions, decay to $\mu^+ + \nu_\mu$
- Magnetic horn focuses charged particles, allows us to select neutrinos or anti-neutrinos
- The NuMI beam has reached its 700 kW design goal, making it the most powerful neutrino beam in the world!



- To date, our exposure is 9×10^{20} protons-on-target (POT) in neutrino mode and 3×10^{20} POT in anti-neutrino mode
- This analysis: 6.05×10^{20} POT

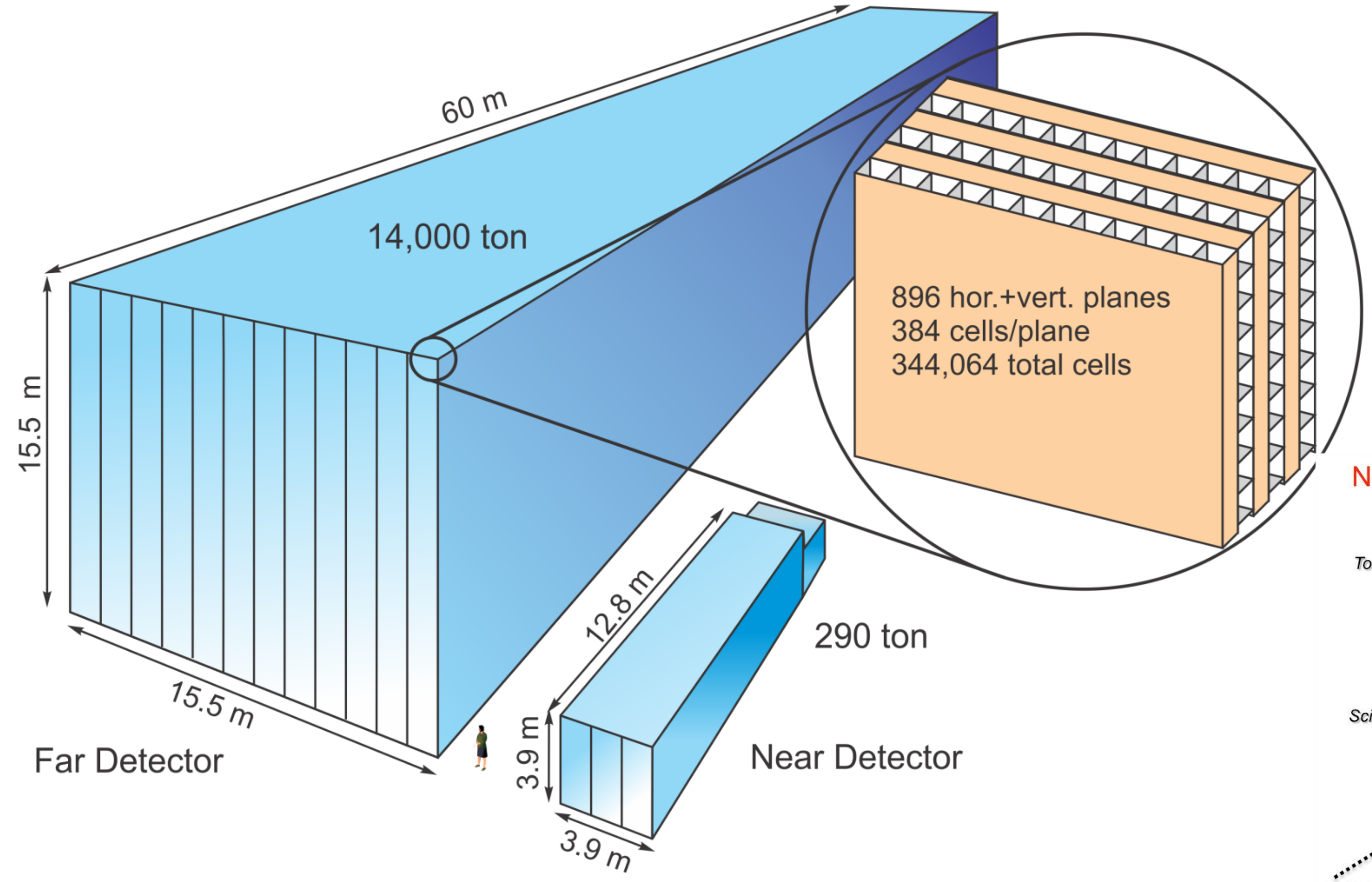
Physics Program

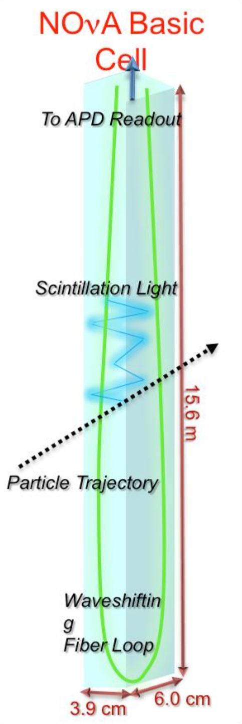
- ν_e appearance ($\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - mass hierarchy
  - θ_{23} octant
  - CPV phase
- ν_μ disappearance ($\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)
  - $\sin^2(\theta_{23})$
  - Δm_{23}^2



- Cross-sections with ND
- Supernova
- Other exotic phenomena
- NC disappearance
  - Limits on Δm_{41}^2, θ_{34}, θ_{24}

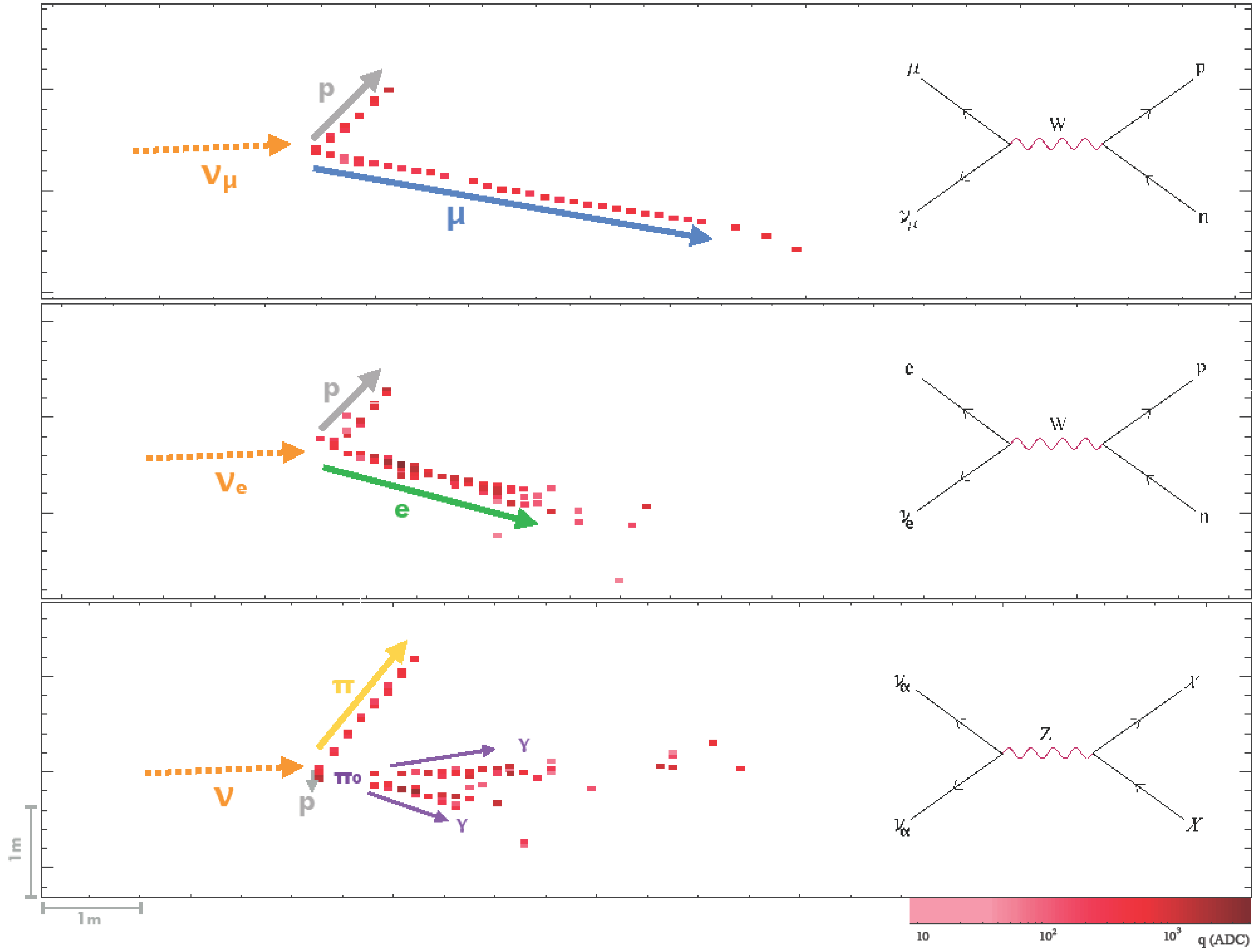
NOvA Detectors





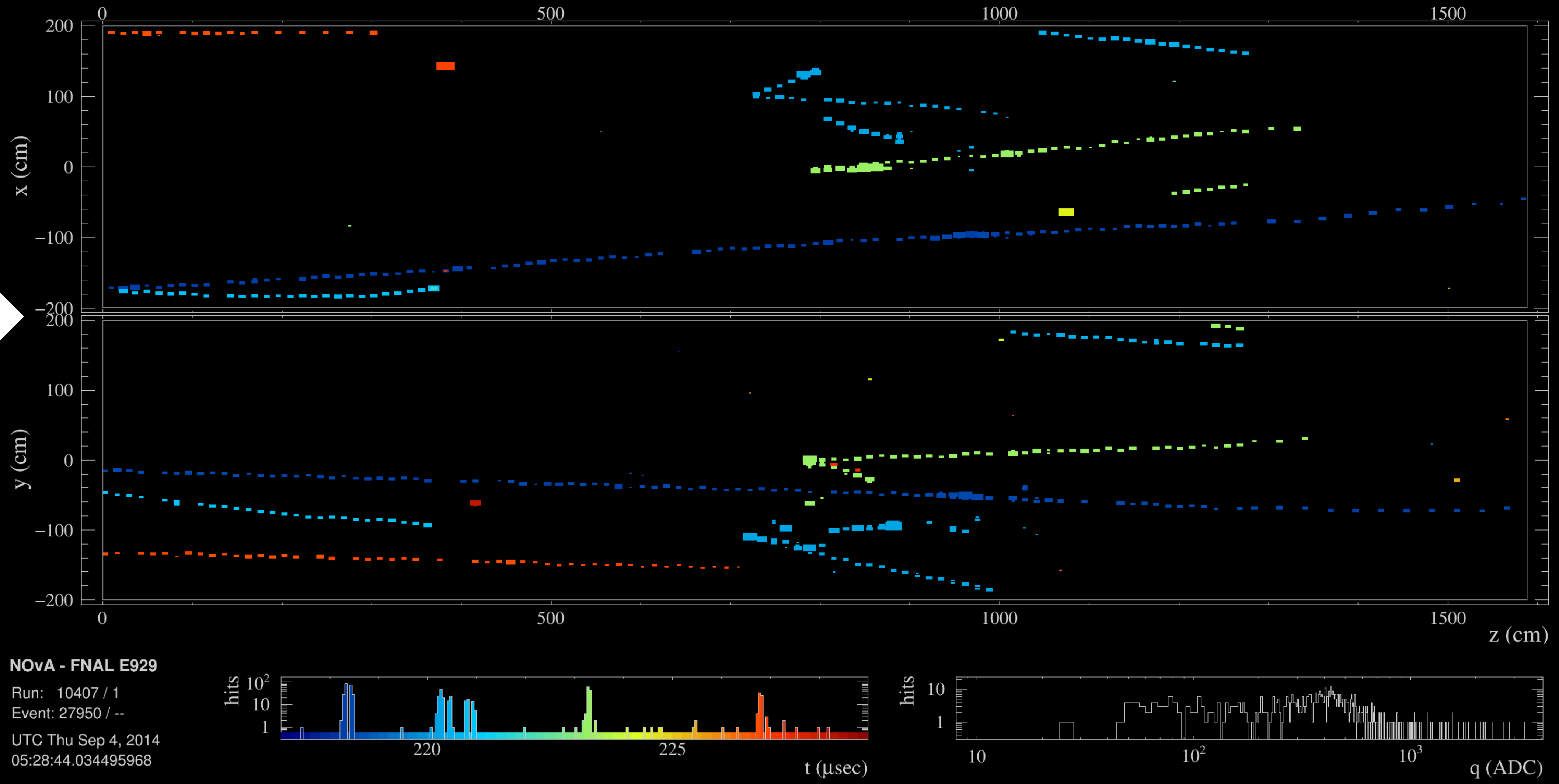
- Low-Z materials: extruded PVC, filled with liquid scintillator
- 4cm x 6cm cells
  - radiation length ~ 40 cm
  - 6 samples per radiation length longitudinally, 3 samples transversely
- 0.7mm wavelength shifting fibers read out to avalanche photodiodes
- Planes of cells are layered, alternating to provide 3D tracking

Event Topologies



Near Detector Event Display

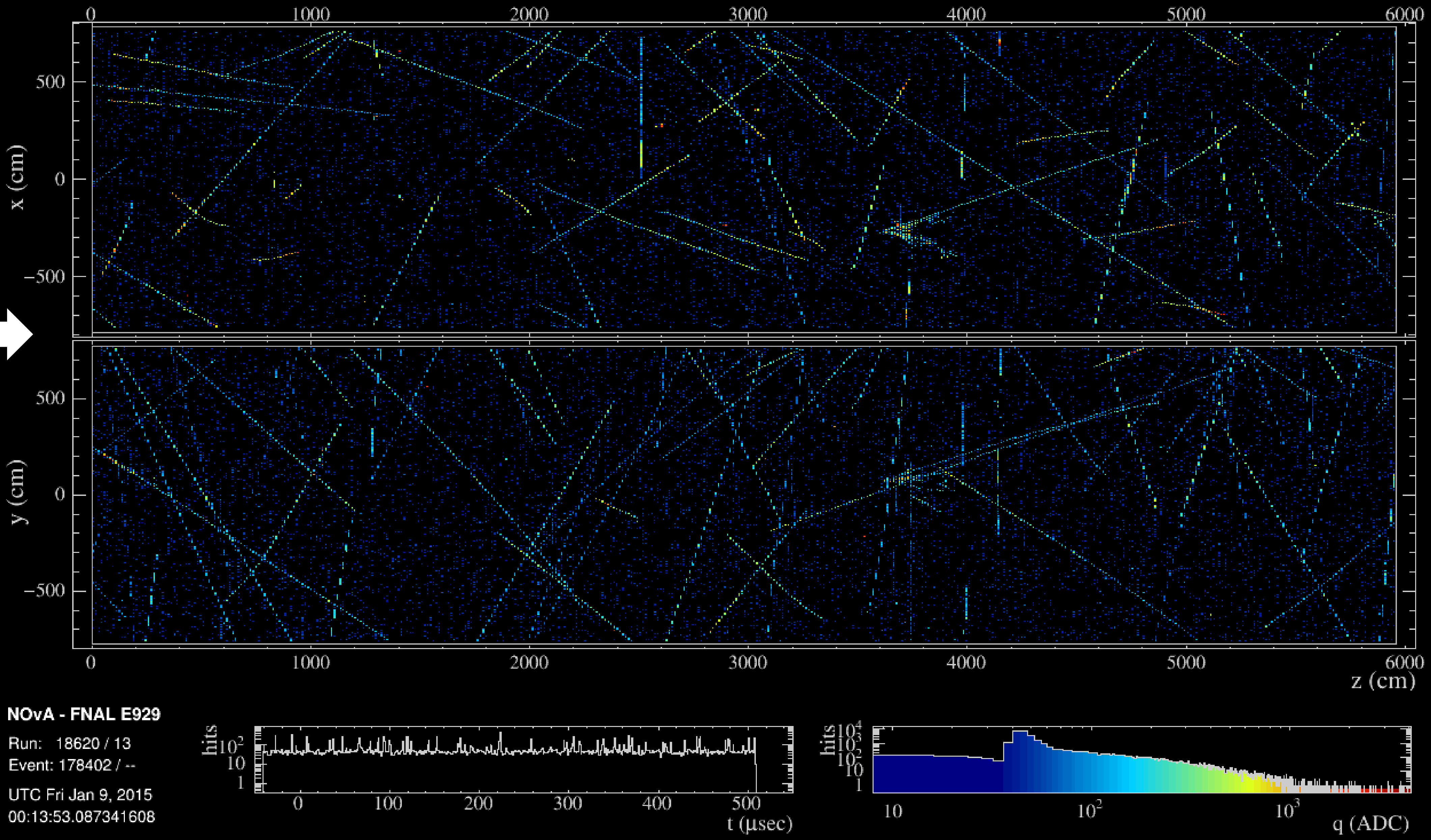
Beam



(colors show hit times)

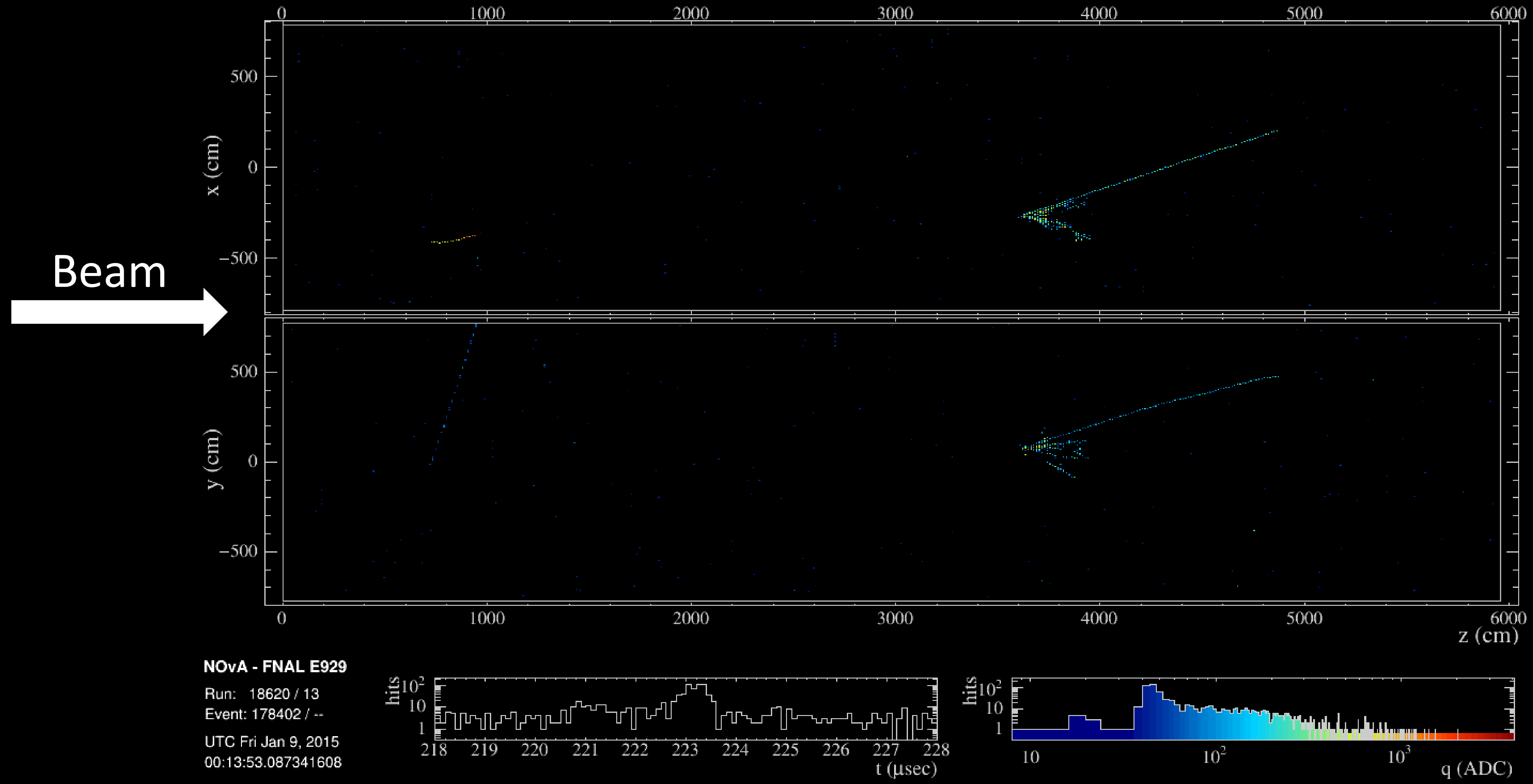
Far Detector Event Display – 550μs

Beam



(colors show charge)

Far Detector Event Display – 10μs



(colors show charge)

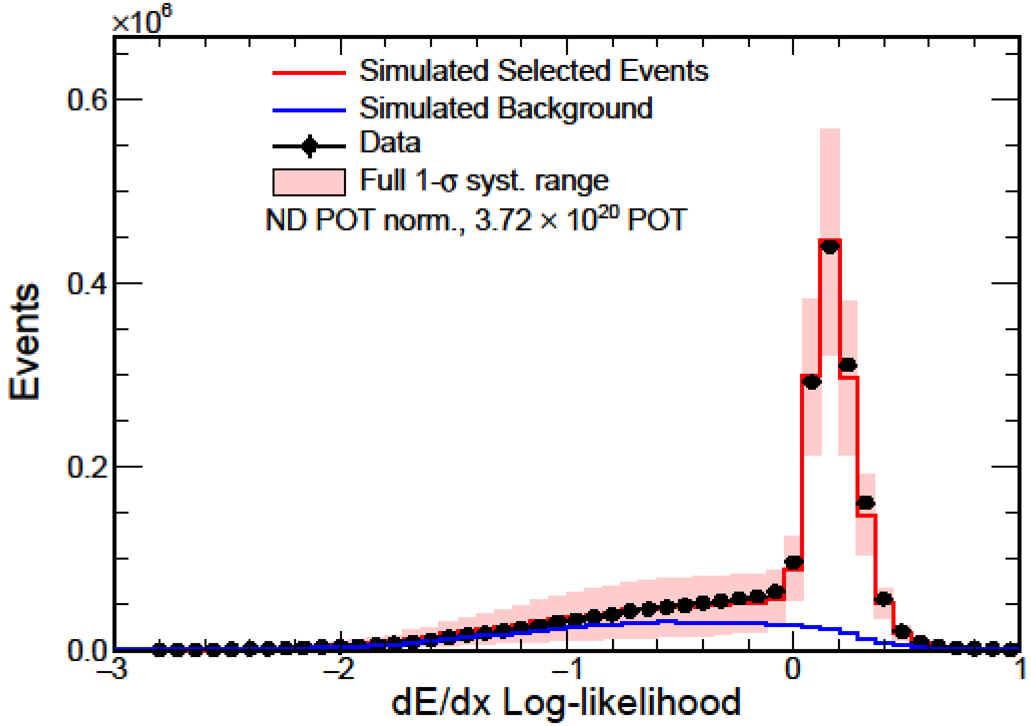
zoomed in on beam window

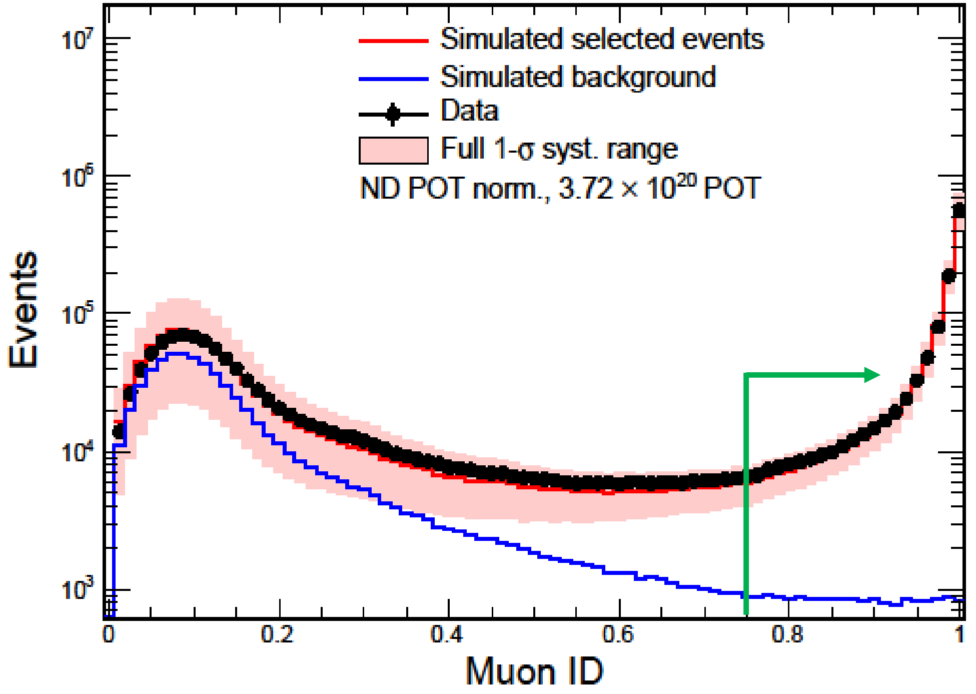
ν_μ disappearance

- $\sin^2(\theta_{23})$
- $\Delta m_{23}{}^2$

Event Selection

- ν_μ events are selected with a traditional kNN
- 4 reconstructed track variables as input
  - track length
  - dE/dx along track
  - scattering along track
  - track-only plane fraction
- Containment cuts remove 99% of the cosmics
- Boosted-decision-tree algorithm that takes input from reconstruction variables rejects the remaining cosmics

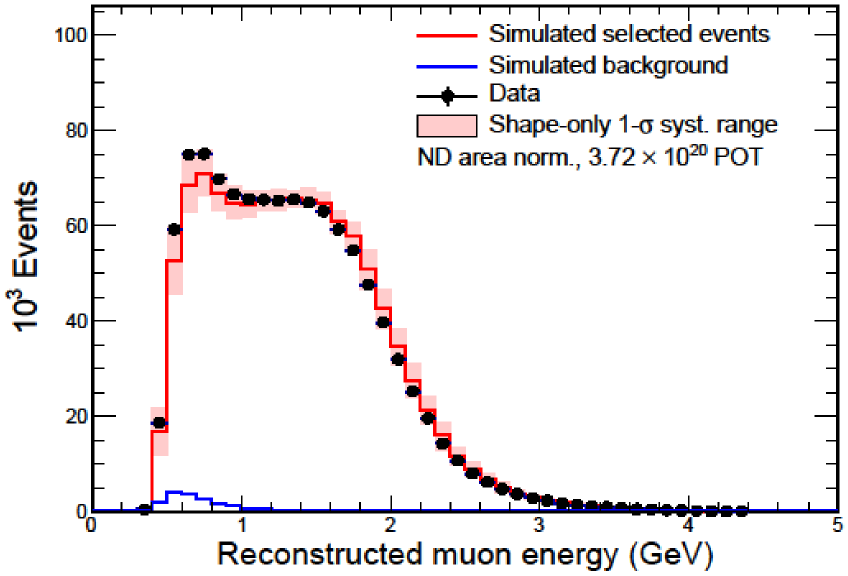


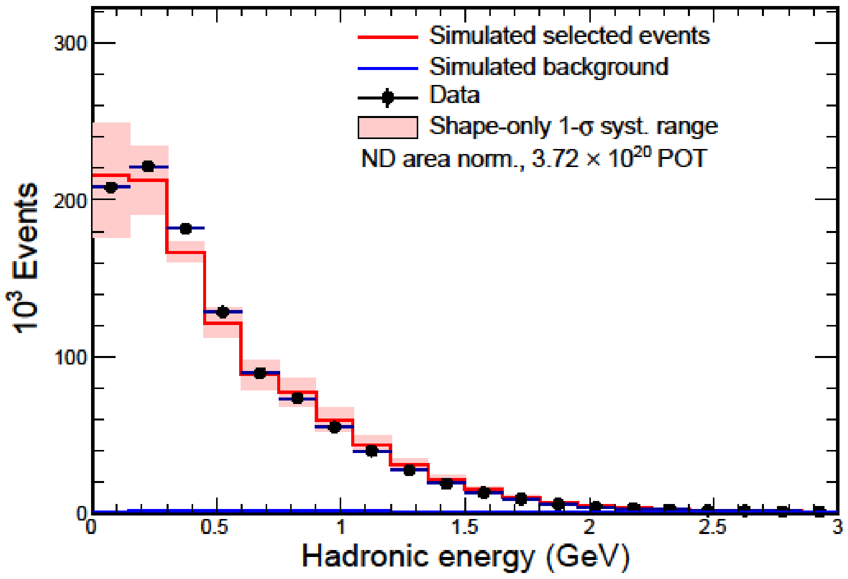


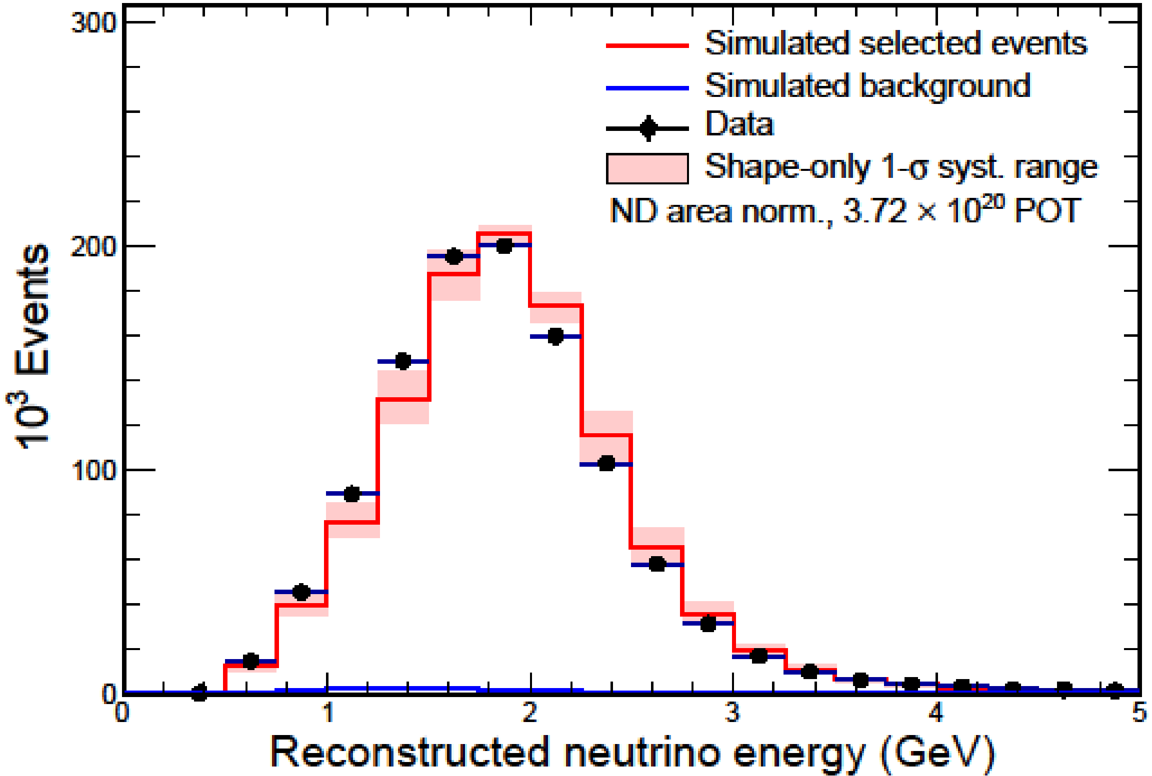
Energy Estimation

- muon length used to calculate energy
- hadronic energy calculated from sum of calorimetric energy of non-muon hits
- $E_\nu = E_\mu + E_{had}$

~7% neutrino energy resolution at beam peak

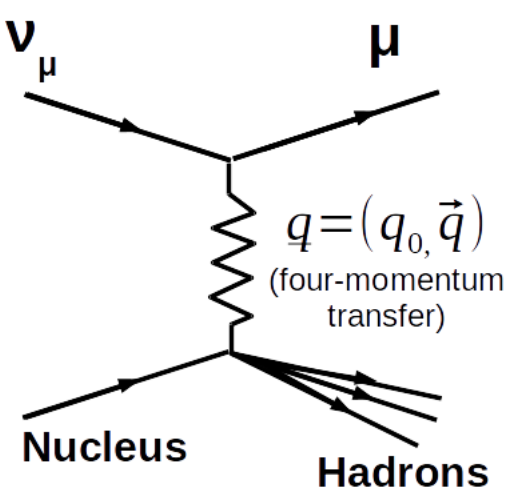


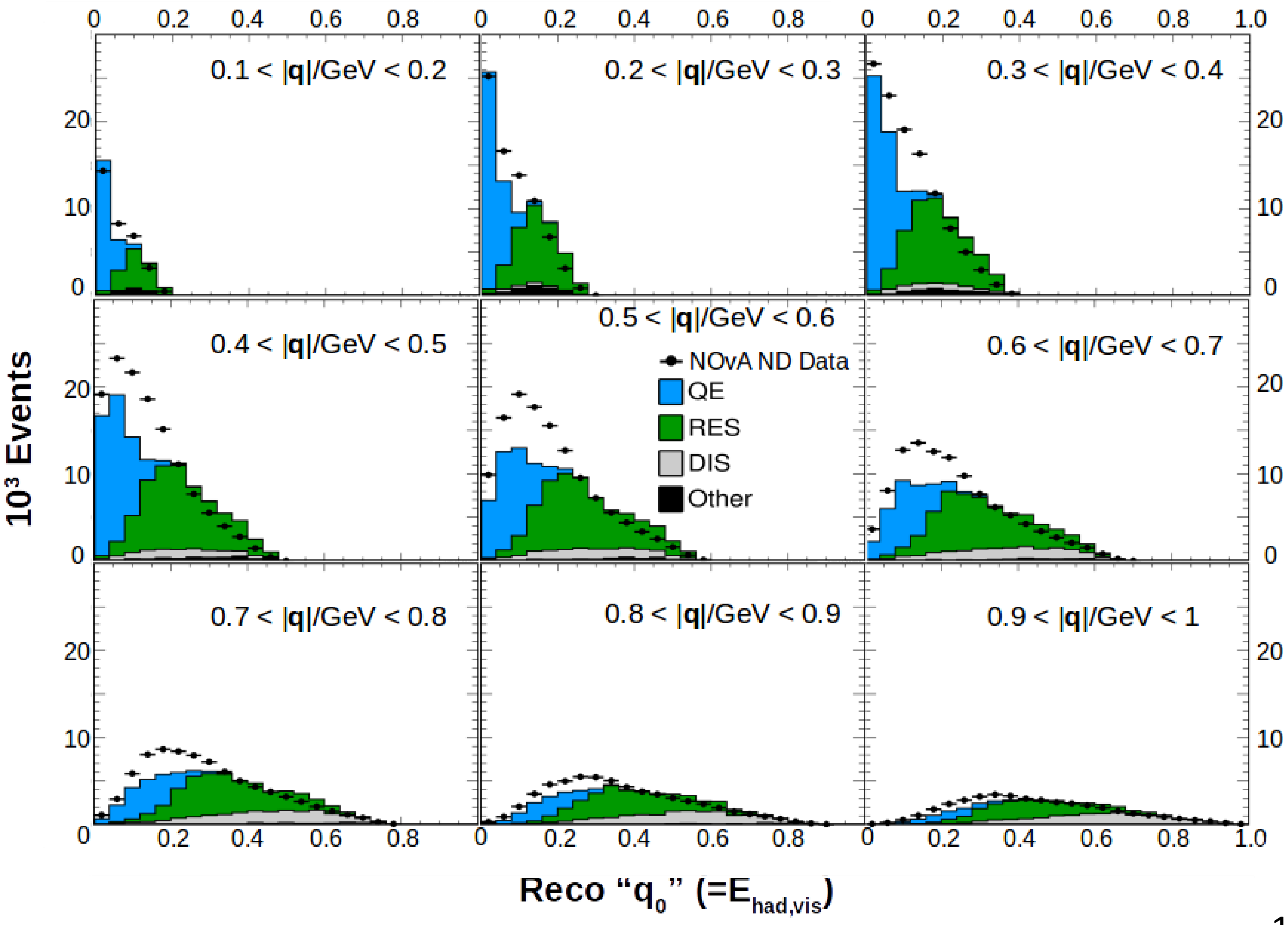




Scattering in a Nuclear Environment

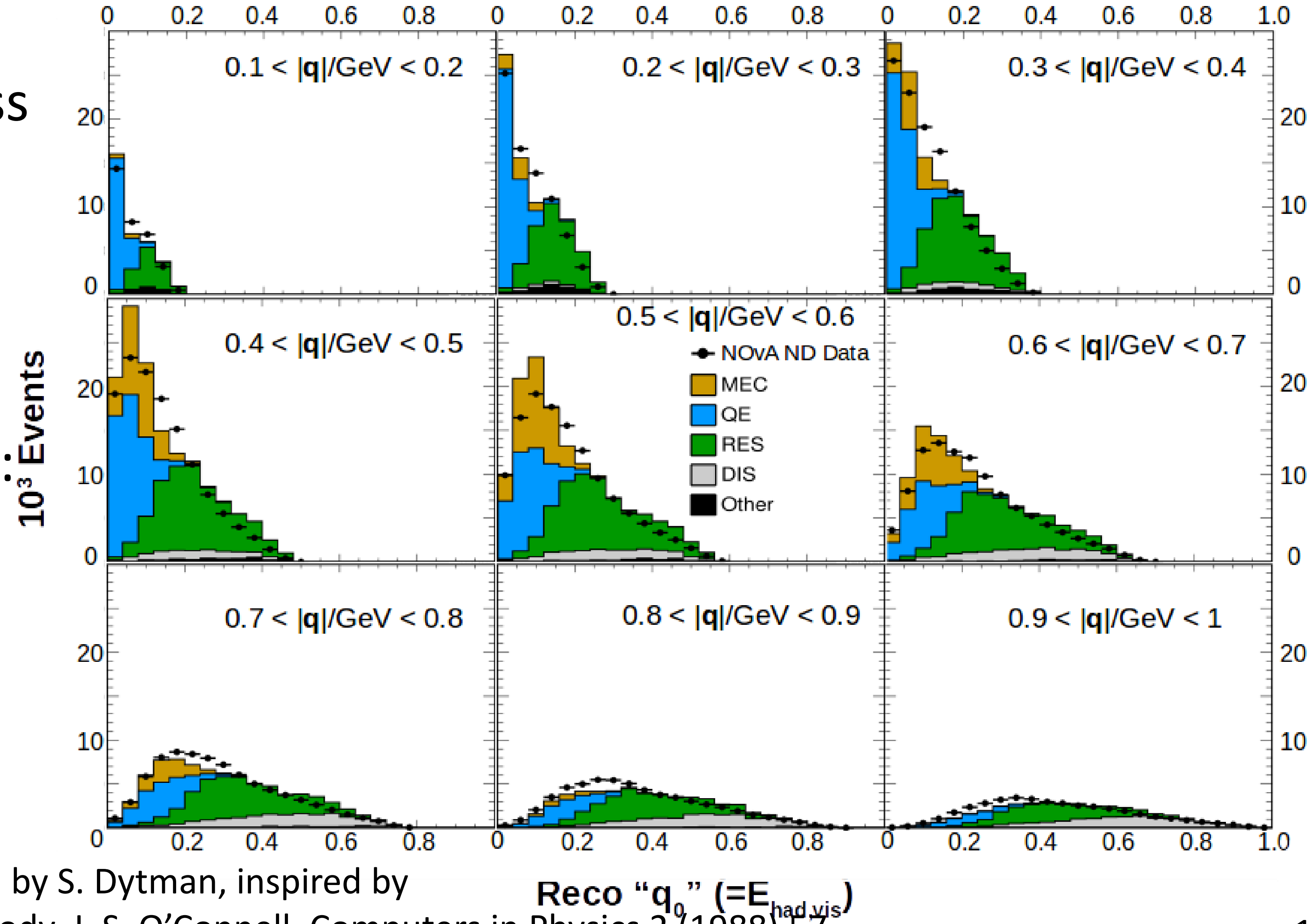
- ND hadronic energy distribution suggested unsimulated process between quasi-elastic and delta production





Scattering in a Nuclear Environment

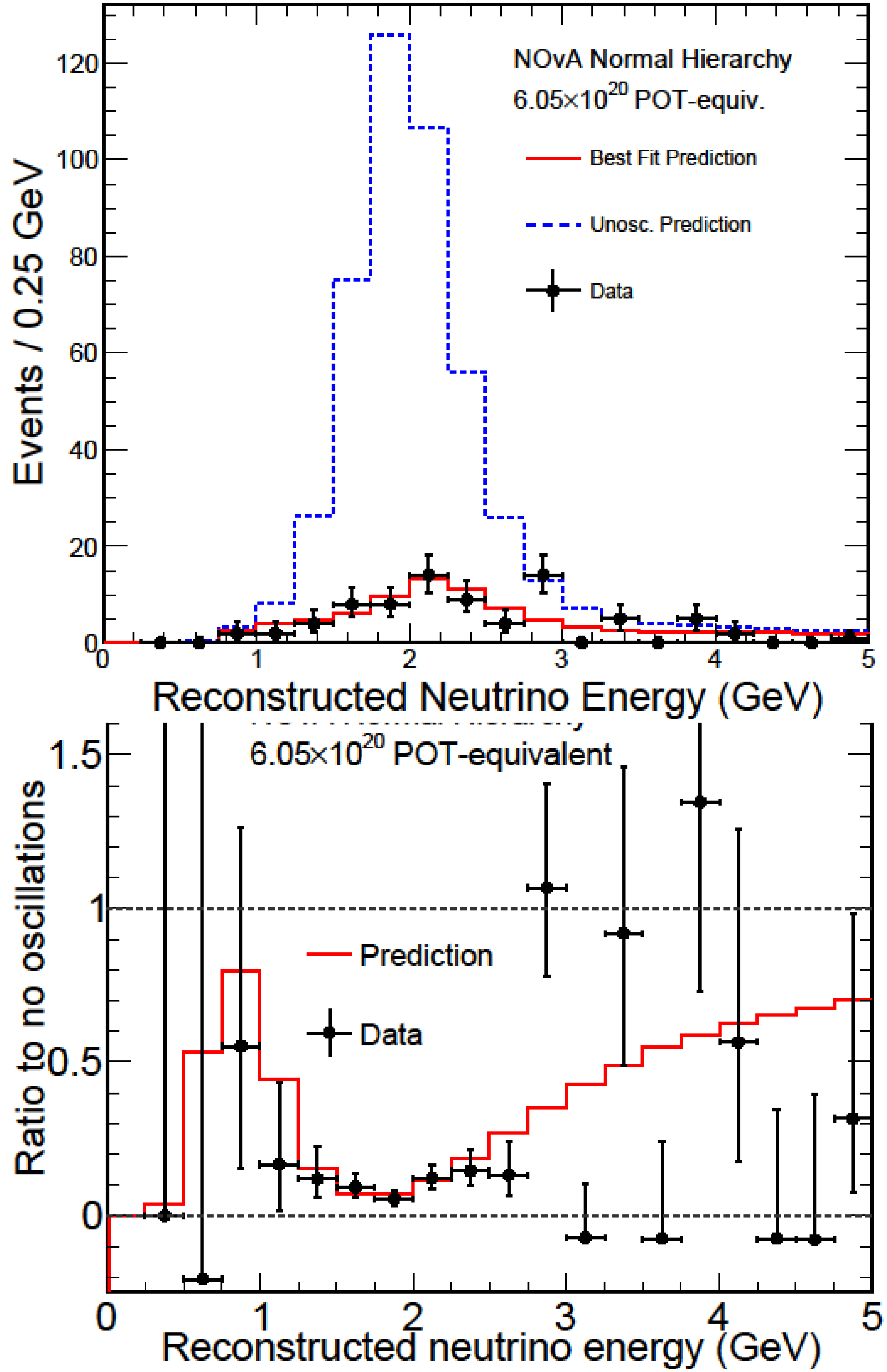
- Enabled GENIE empirical Meson Exchange Current model
- Reweight to match NOvA excess as a function of 3-momentum transfer
- 50% systematic uncertainty on MEC component
  - Reduces largest systematics: hadronic energy scale, QE cross section modeling
- Reduce single non-resonant pion production by 50%



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

ν_μ Disappearance Results

- 78 events selected in FD (0-5 GeV) including 2.9 cosmics, 3.7 beam bkg
- No oscillations: 473 +/- 30 expected



ν_μ Disappearance Results

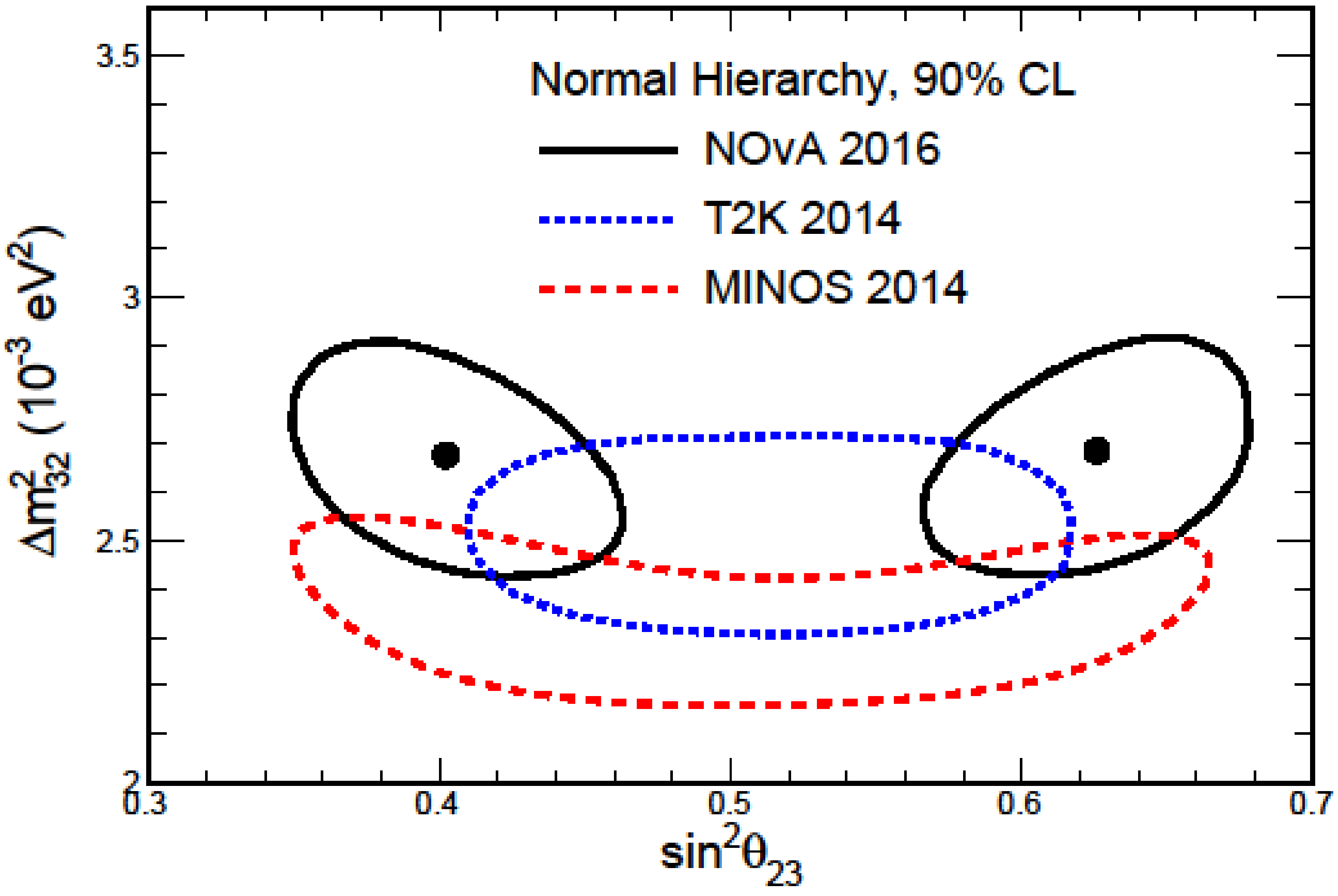
P. Adamson *et al.* (NOvA Collaboration)
Phys. Rev. Lett. **118**, 151802 (2017)

Best fit (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 disfavored at 2.6σ



Neutral Current Disappearance

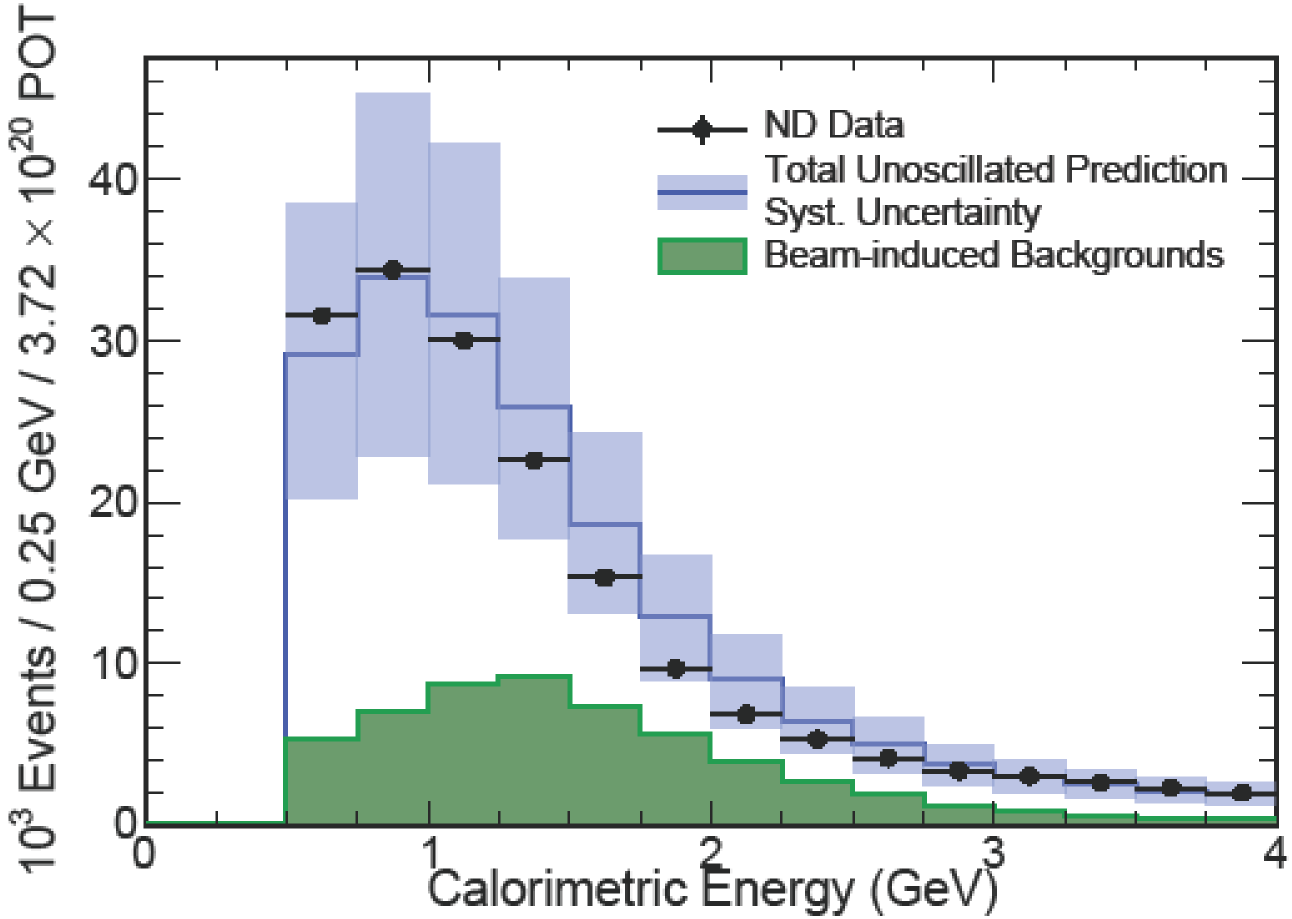
Δm_{41}^2, θ_{34}, θ_{24}

NC Results

arXiv1706.04592

- Sterile neutrino oscillations could deplete the NC rate at the far detector

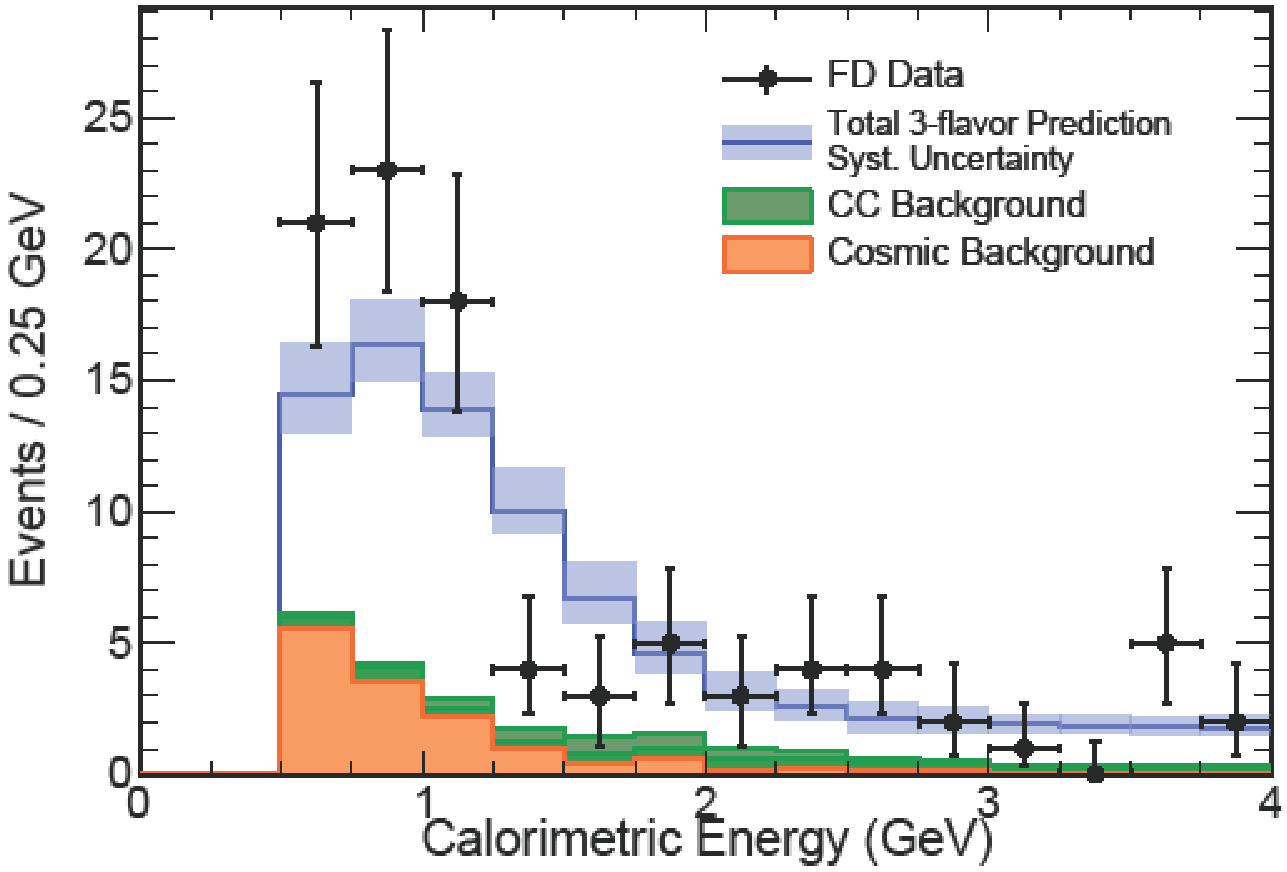
- Rate-only analysis
- FD rate predicted from calorimetric energy for NC-selected events
- Data/MC discrepancies from simulations and detector response
  - Accounted for by FD prediction technique
  - Remaining differences absorbed in systematic uncertainties
  - MEC has since been included in this analysis



NC Results

arXiv1706.04592

- Extrapolation predicts 83.5 events under 3 flavor assumption
- Observe 95
- 1.03 sigma excess over 3 flavor prediction
- No evidence of oscillation involving steriles



NC Results

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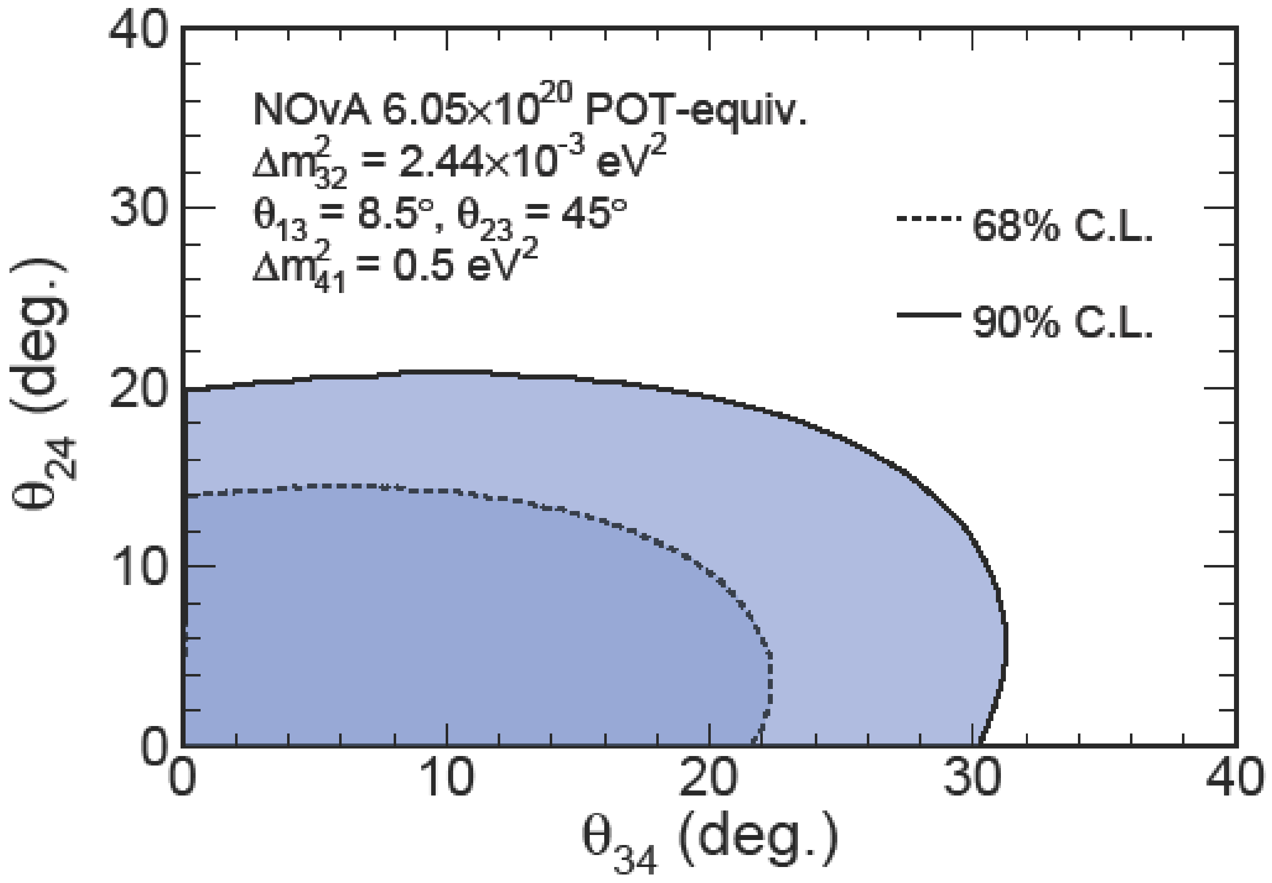
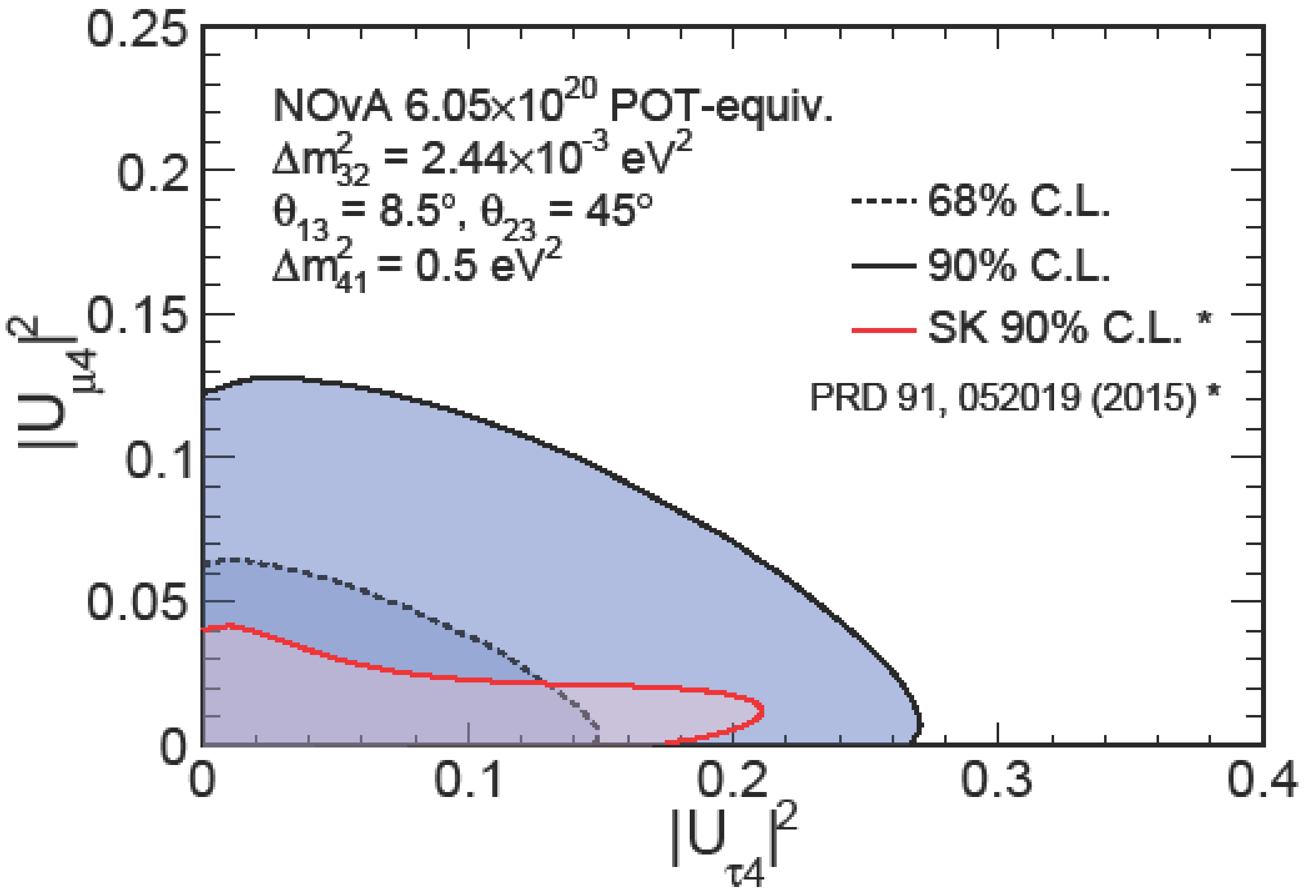




For $0.05 \text{ eV}^2 < \Delta m^2_{41} < 0.5 \text{ eV}^2$

$\theta_{34} < 35°, \ \theta_{24} < 21° \ (90\%\text{C.L.})$

$|U_{\mu 4}|^2 < 0.126$ and $|U_{\tau 4}|^2 < 0.268$

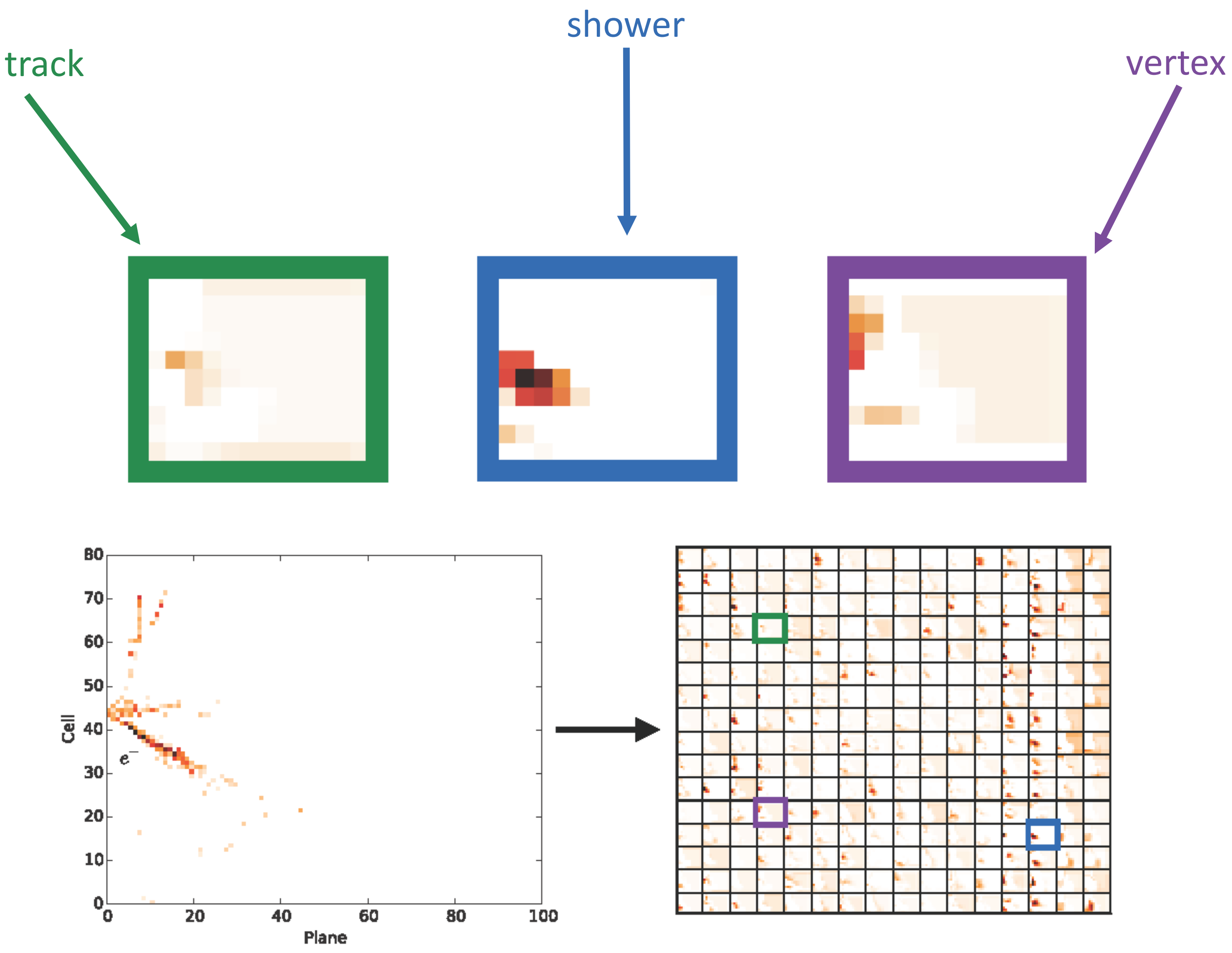
ν_e appearance

- mass hierarchy
- θ_{23} octant
- CPV phase

Event Selection

A. Aurisano et. al., JINST 11 (2016) no.09, P09001

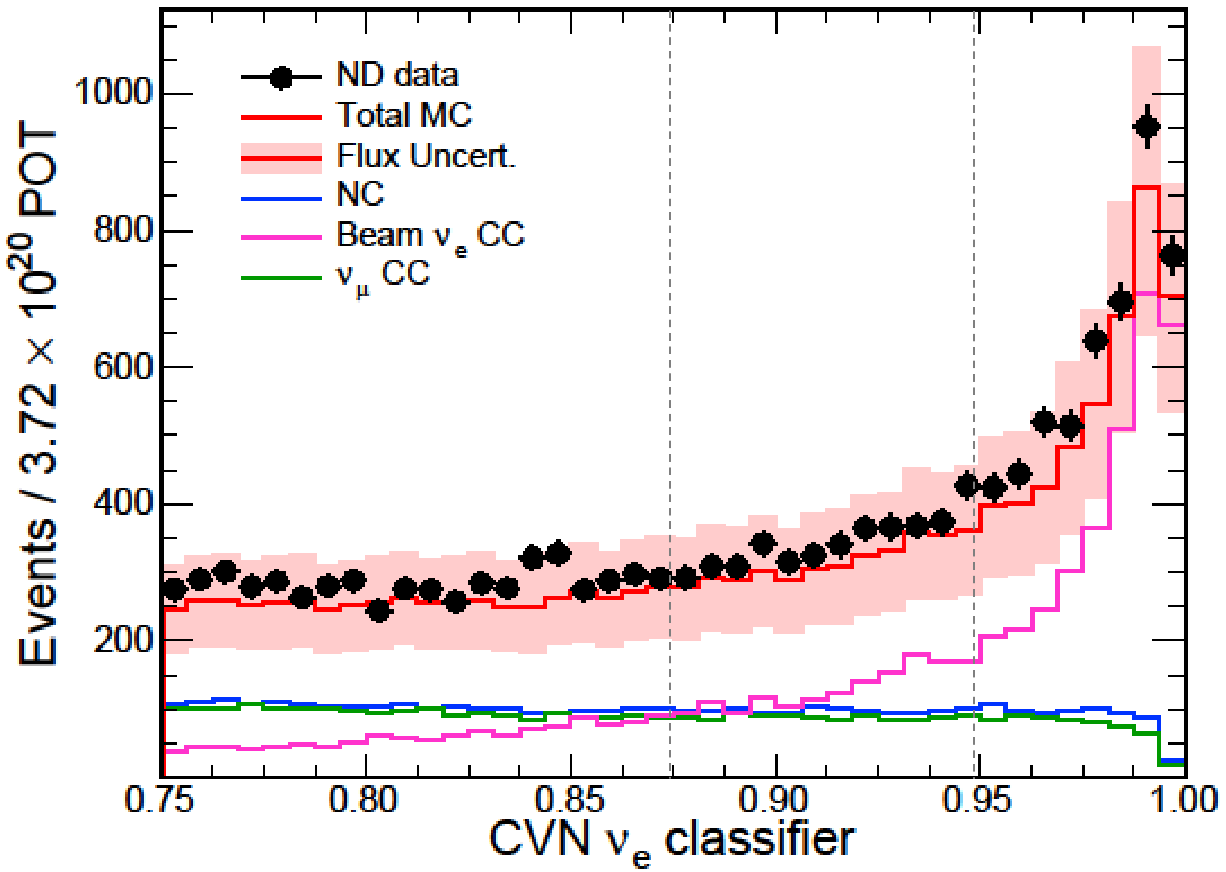
- Signal identification done by our CVN (convolutional visual network)
  - Classifier that employs a Deep Convolutional Network in the "image recognition" style
  - trained on 2D views of the event's calibrated hits
  - Information of each view is combined in the final layers of the network

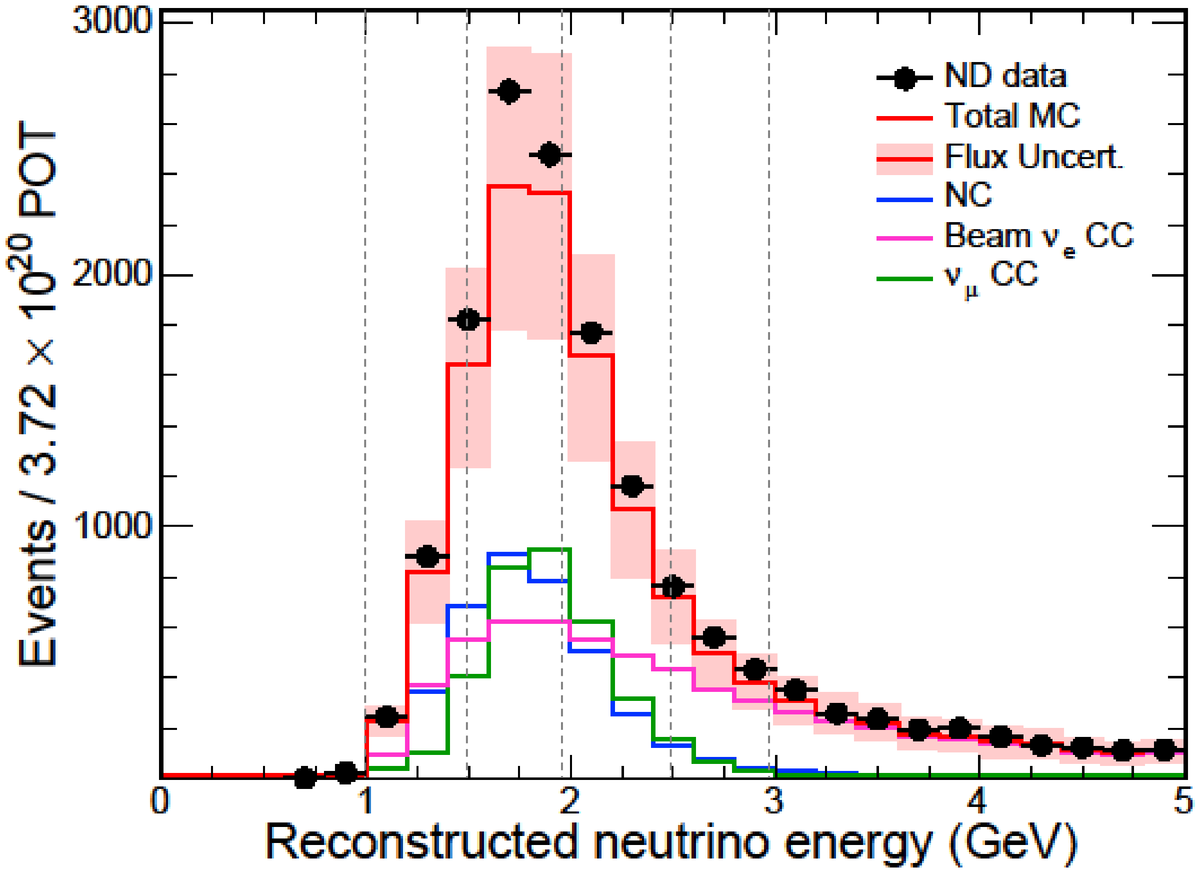


electron neutrino interaction and first layer of feature maps - strong feature is the shower

Event Selection

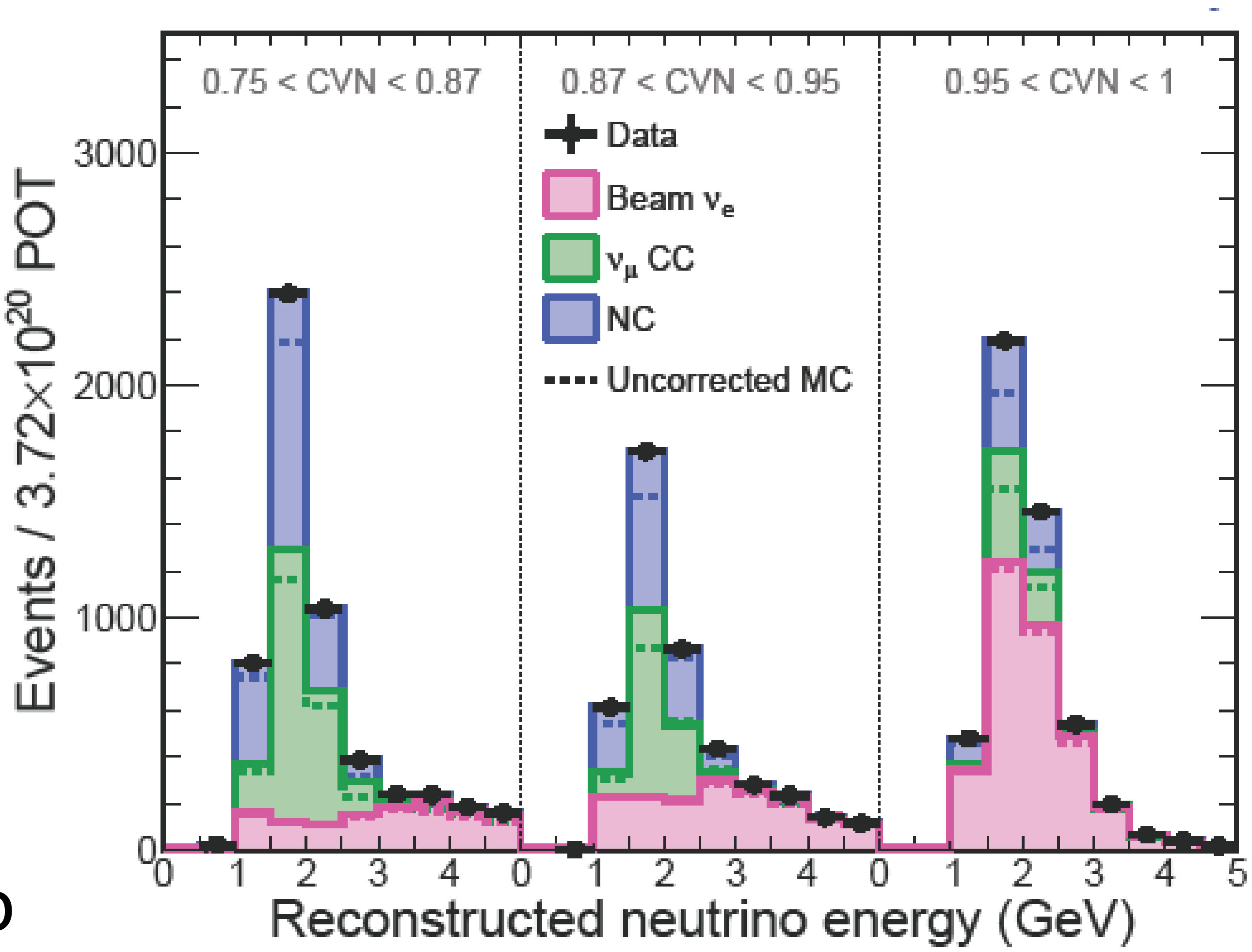
- selection optimized to maximize $FOM = S/\sqrt{S+B}$ including cosmic rejection and classifier cuts
- analysis binned in 3 PID bins, 4 energy bins





Data driven background corrections

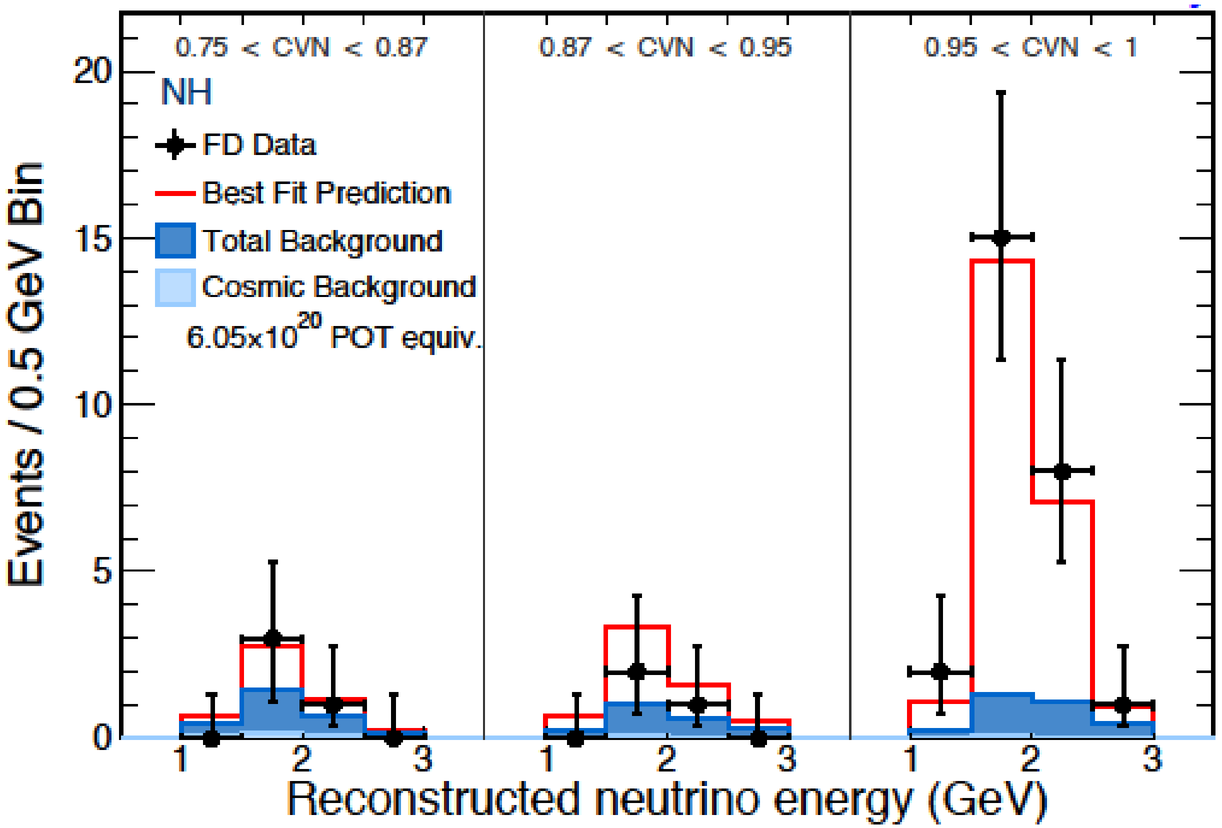
- ND selection picks out FD backgrounds:
  - beam ν_e
  - ν_μ CC
  - NC
- ~10% excess of data over MC in ND
- extrapolate data/MC differences to adjust FD prediction
- each component oscillates differently – must decompose into individual components

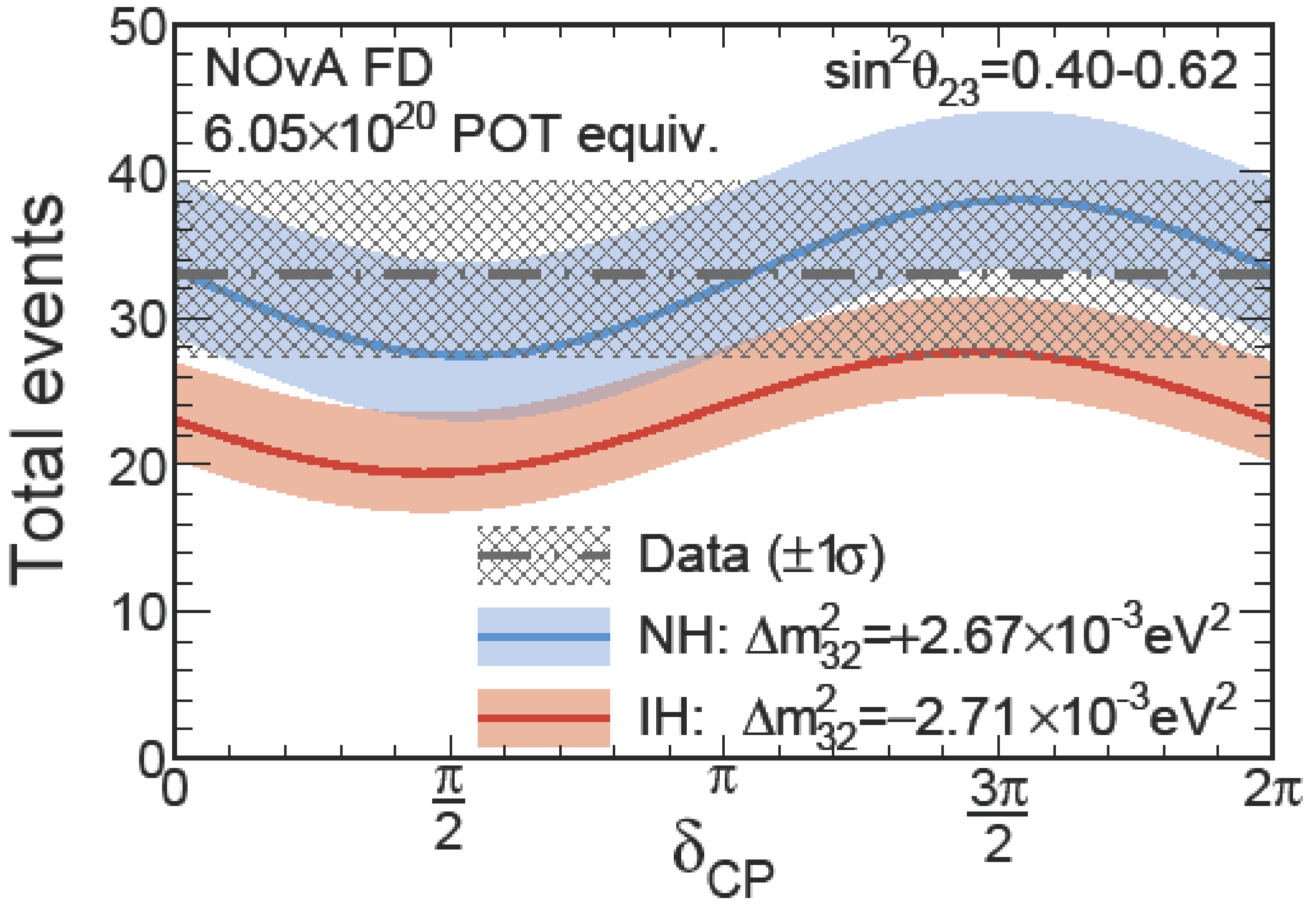


ν_e Appearance Results

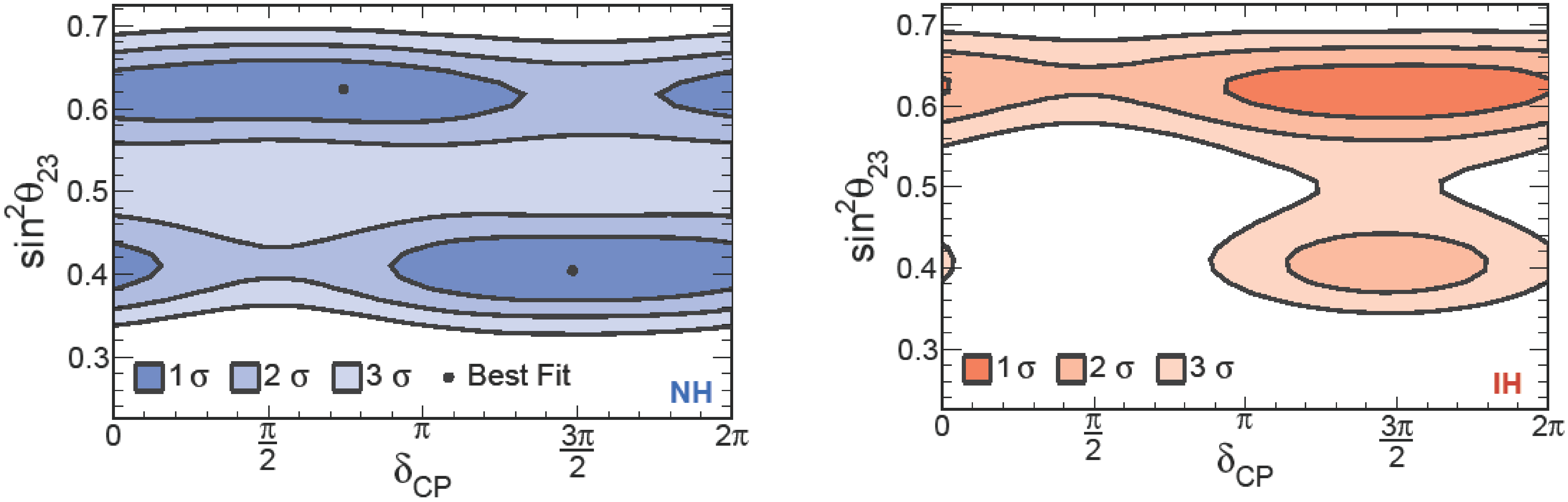
P. Adamson *et al.* (NOvA Collaboration)
Phys. Rev. Lett. **118**, 231801 (2017)

- 33 ν_e candidates observed
- background of 8.2 events
- 8σ significant excess over bkg





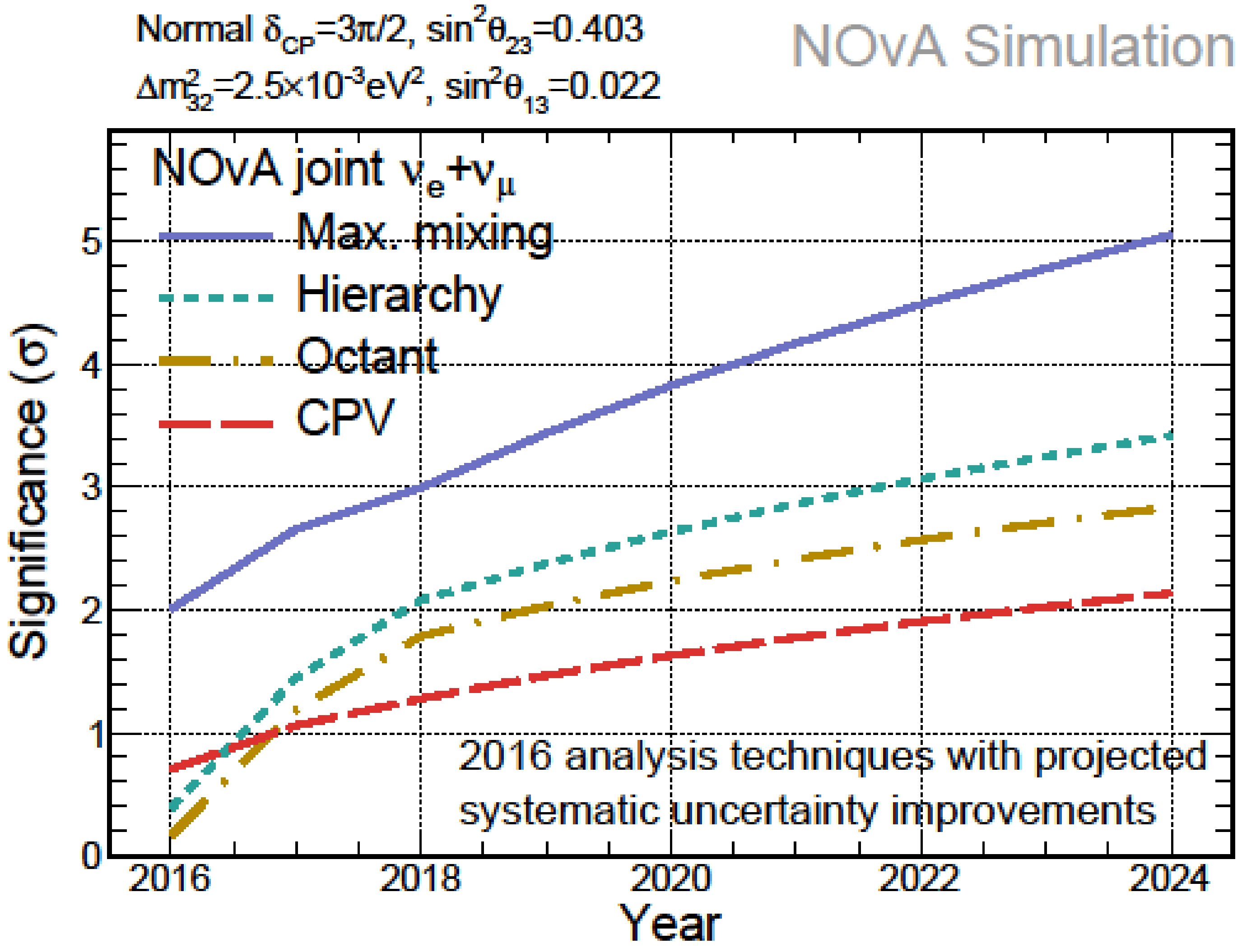
ν_e Appearance Results



- Constrain Δm^2 and $\sin^2\theta_{23}$ with ν_μ disappearance
- Constrain $\sin^2(2\theta_{13}) = 0.085 +/- 0.005$ (reactor)
- Global best fit: $\delta_{CP} = 1.48\pi$, $\sin^2\theta_{23} = 0.404$; $\delta_{CP} = 0.74\pi$, $\sin^2\theta_{23} = 0.623$
- IH, $\delta_{CP} < \sim\pi/2$ rejected (3σ) for lower octant

Outlook

- Switched to anti-neutrino mode February 2017
- Plan to run 50% neutrino, 50% anti-neutrino mode after 2018
- With extended running and planned proton intensity improvements through Fermilab PIP-1 upgrades:
  - 3σ sensitivity to maximal mixing of θ_{23} in 2018
  - 2σ sensitivity to mass hierarchy and θ_{23} octant in 2018-2019



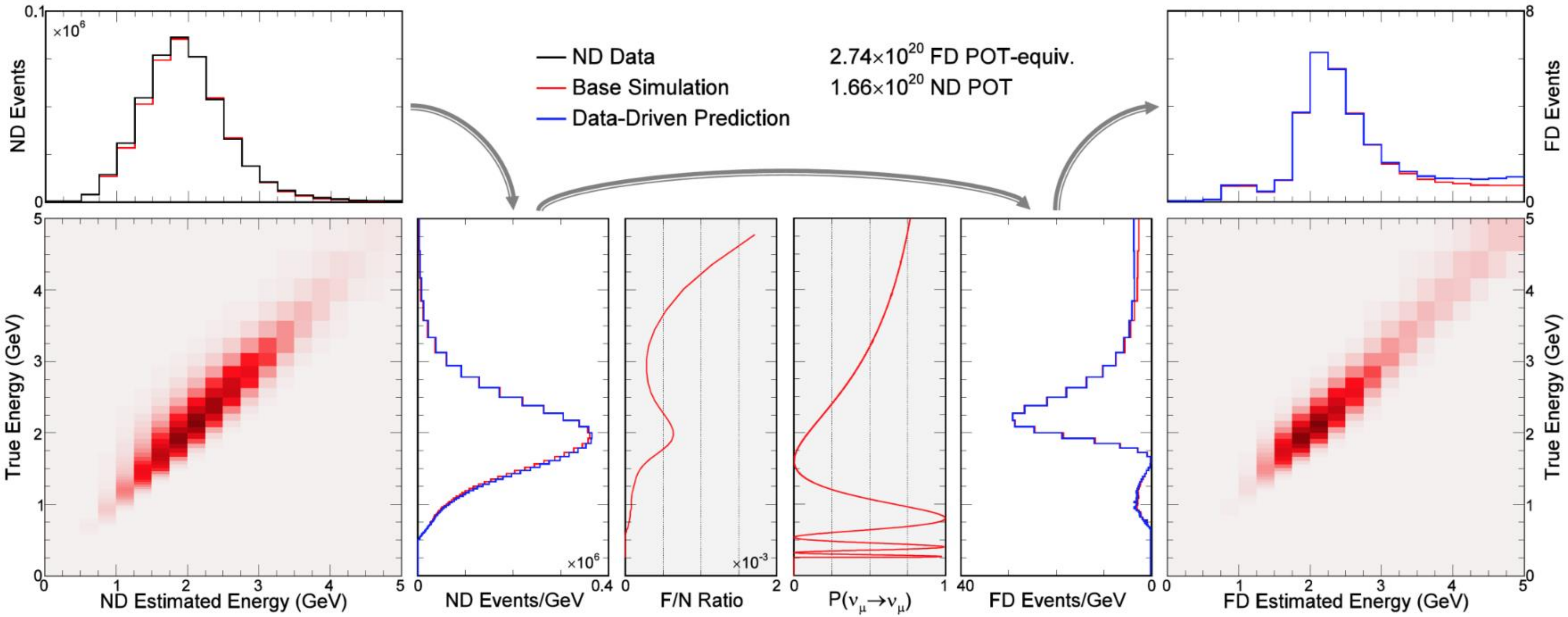
Summary

- 6.05 x 10^{20} POT of NOvA data
- ν_μ disappearance
  - Best fit is non-maximal θ_{23}
  - Maximal mixing disfavored at 2.6σ
- ν_e appearance
  - Slight preference for normal hierarchy
  - Inverted hierarchy, δ_{CP} ~π/2 rejected for lower octant
- NC appearance
  - No evidence for oscillations involving sterile neutrinos
- Started anti-neutrino running in February

Thank you!

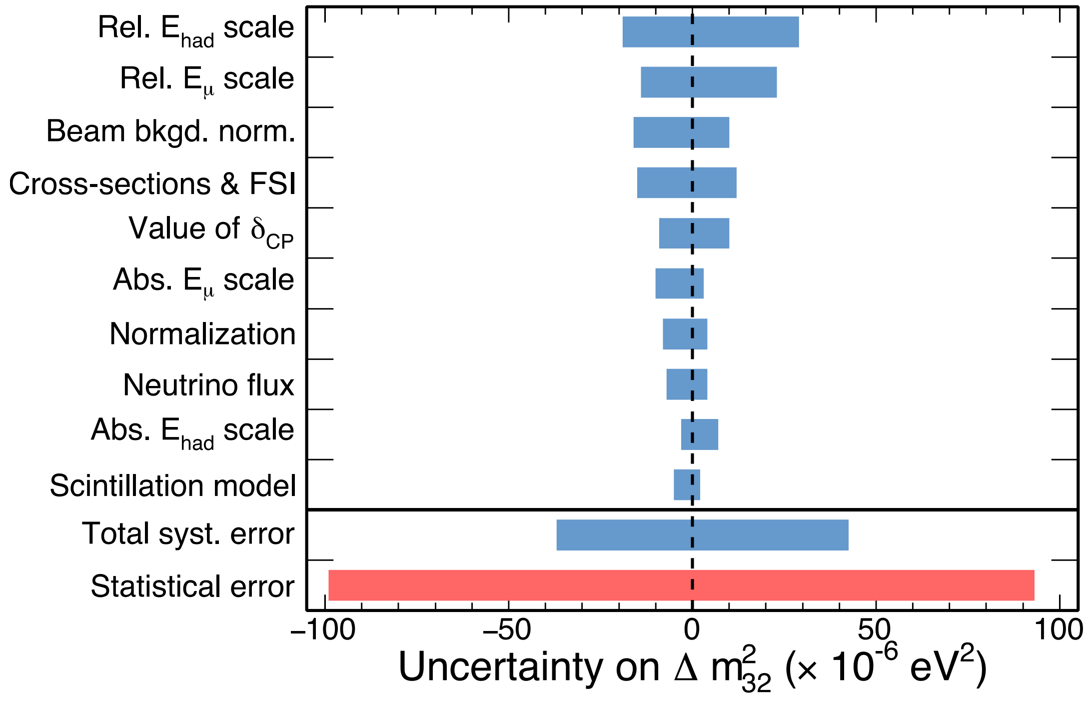
Extrapolation

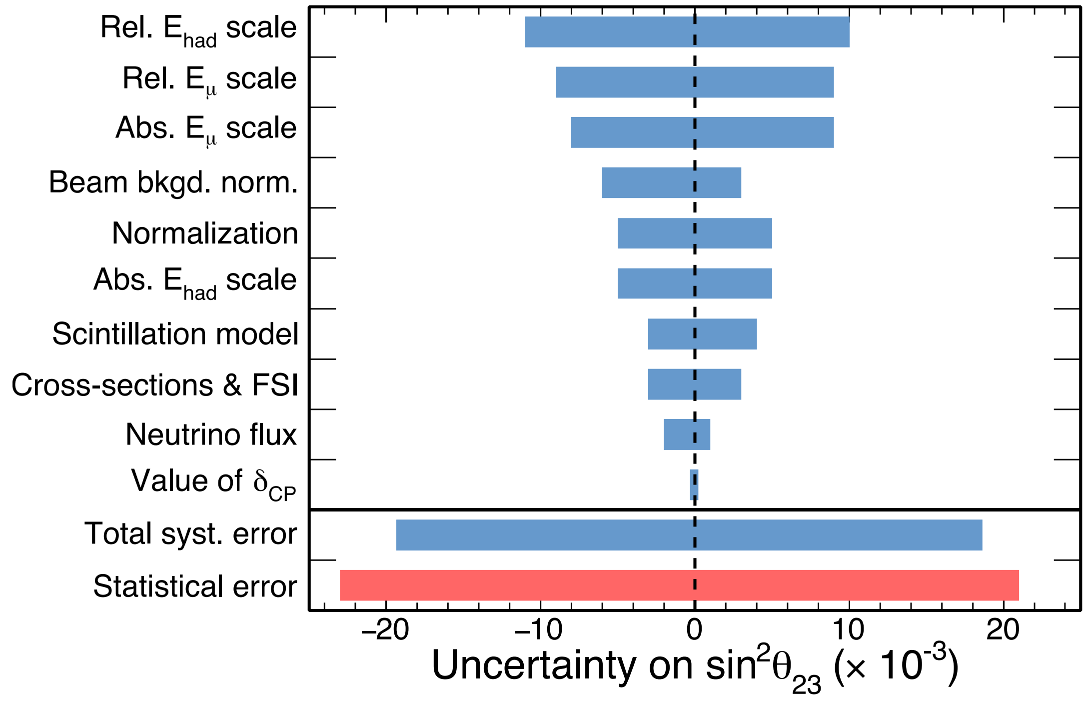
- estimate underlying true energy distribution of ND events
- multiply by F/N event ratio and oscillation probability
- convert FD true energy distribution into predicted FD reco energy distribution



Numu 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





Nue Systematics

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

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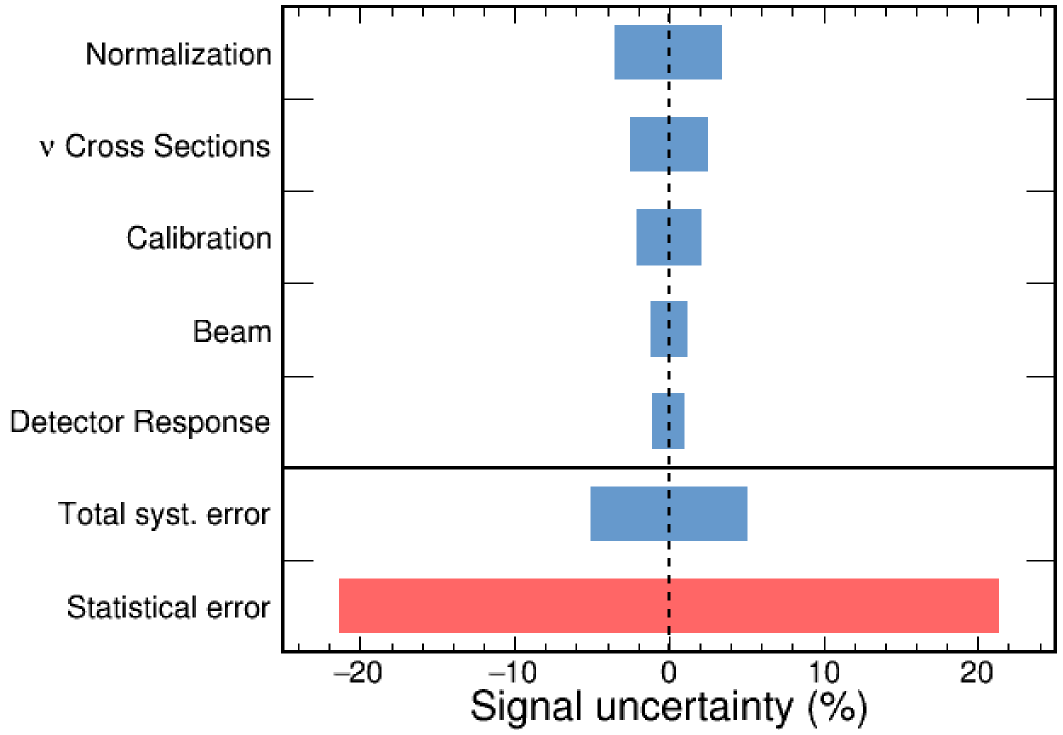
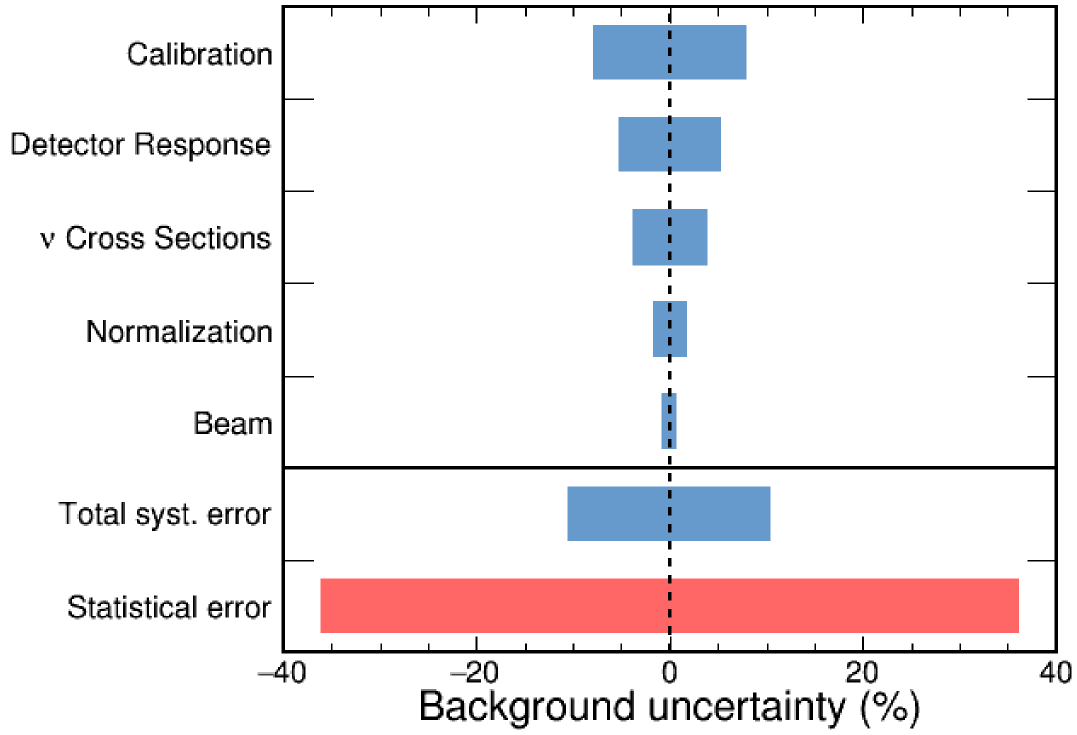
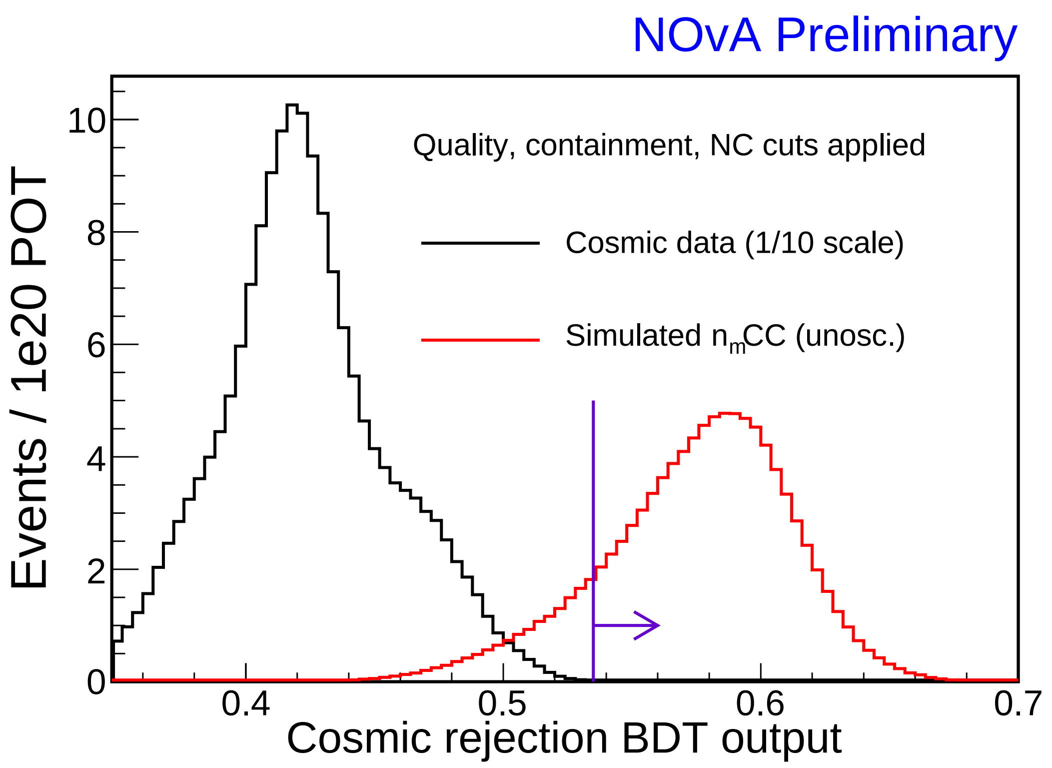
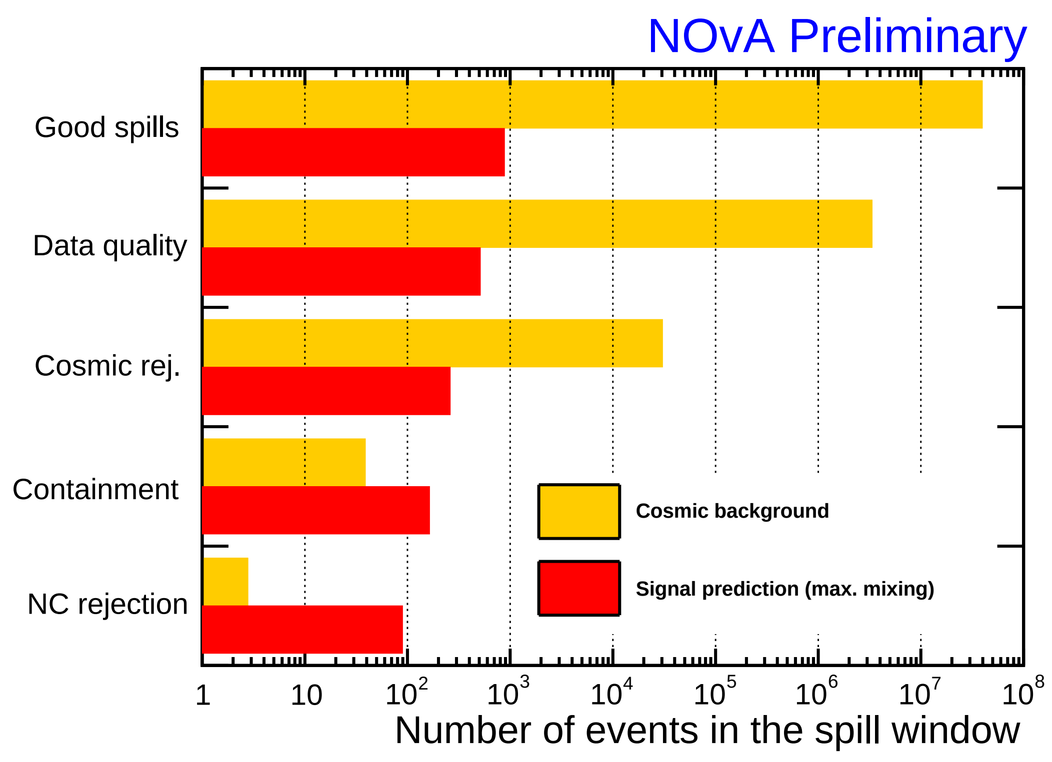




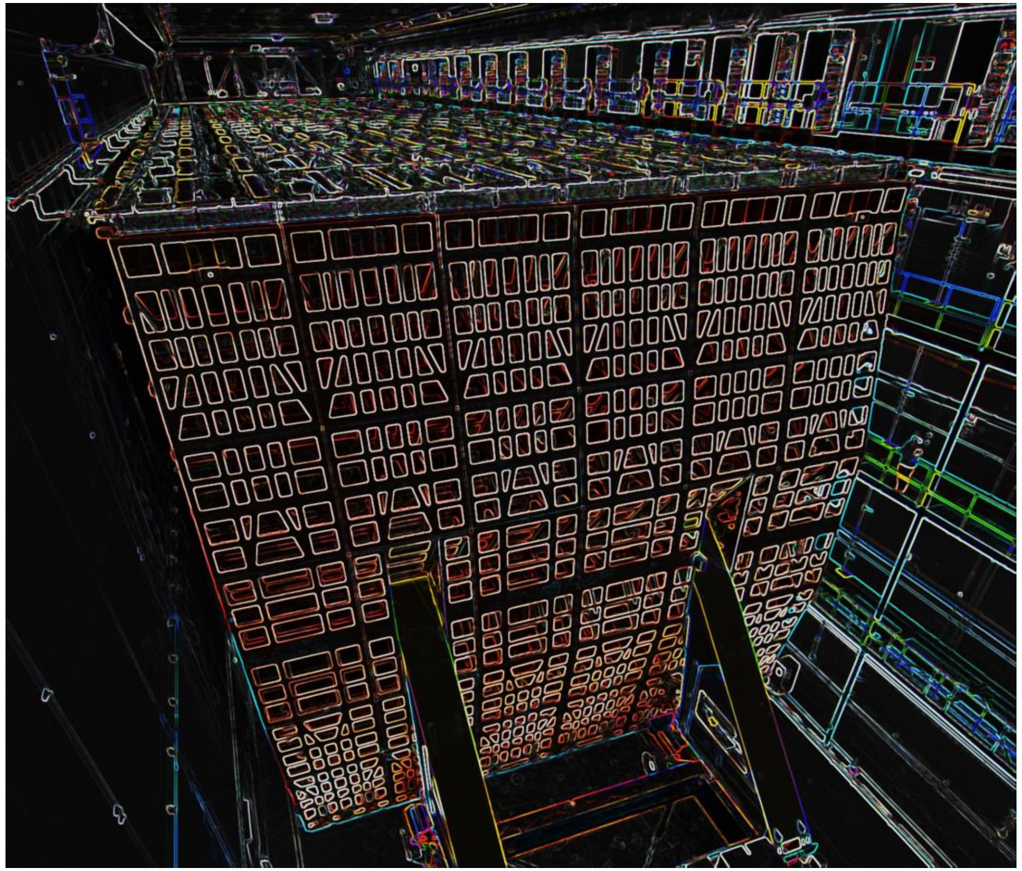
Cosmic Rejection

- Expect ~65,000 cosmic rays in-time with the NuMI beam spills per day
- Containment cuts remove 99% of the cosmics.
- Boosted-decision-tree algorithm that takes input from reconstruction variables rejects the remaining cosmics
- 2.9 cosmics in 6.05 x 10^{20} POT



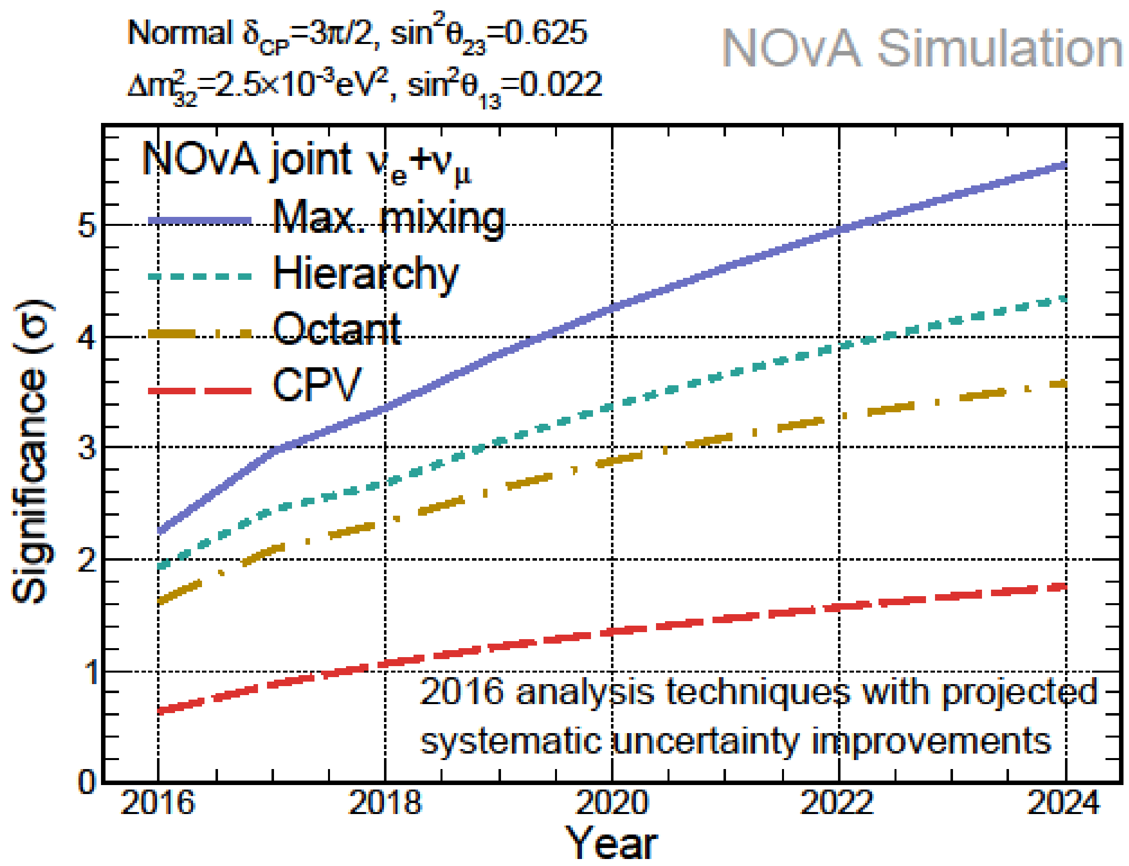


Event Selection



- 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

Outlook

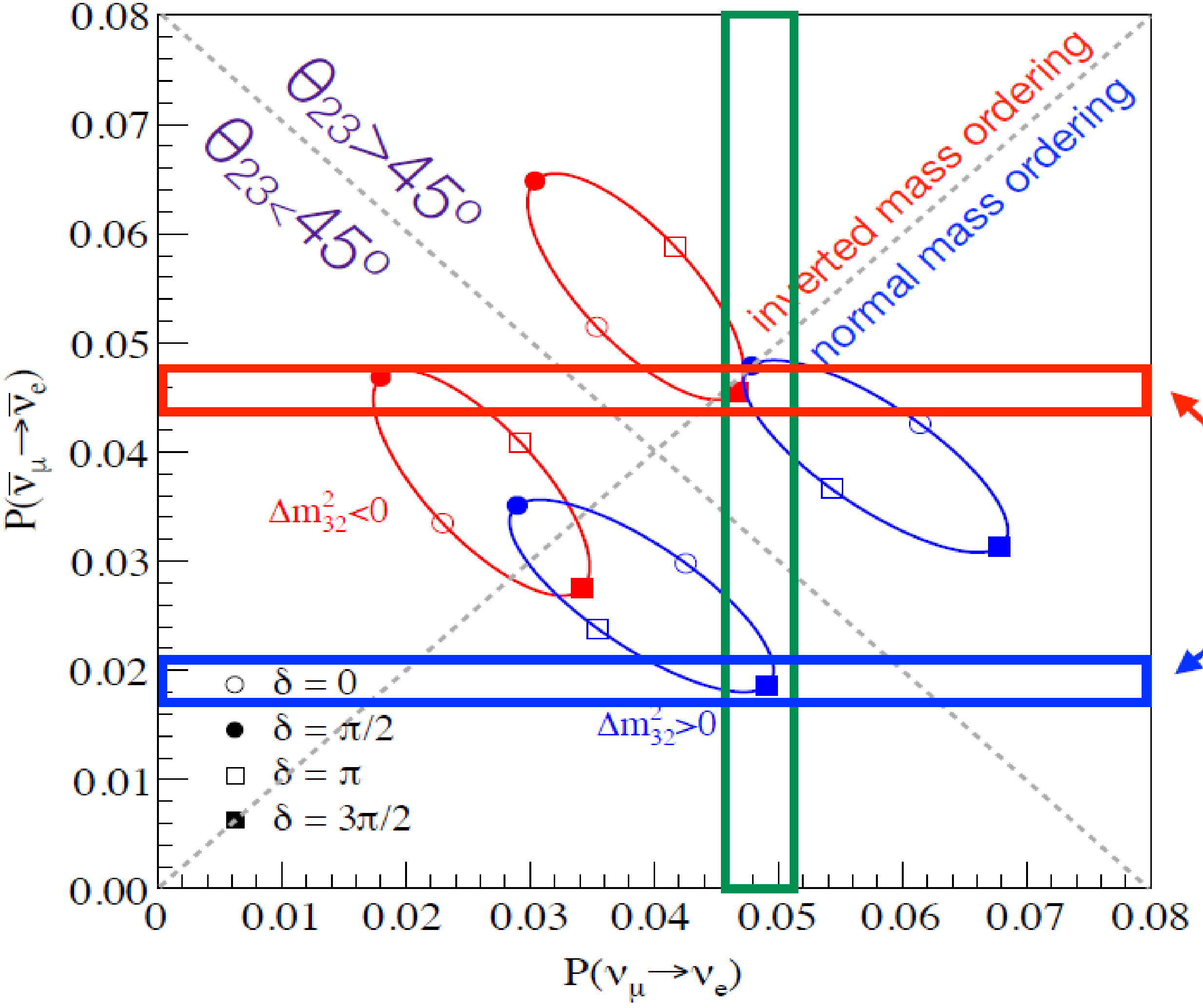


- switched to anti-neutrino mode February 2017
- plan to run 50% neutrino, 50% anti-neutrino mode after 2018
- 3σ sensitivity to maximal mixing of θ_{23} in 2018
- 2σ sensitivity to mass hierarchy and θ_{23} octant in 2018-2019

Outlook

Need for antineutrinos:
If we are in lower octant, normal hierarchy, antineutrinos are required.

If we are here in neutrinos



we need antineutrinos to know if we are here or here

$\bar{\nu}_e$ Appearance