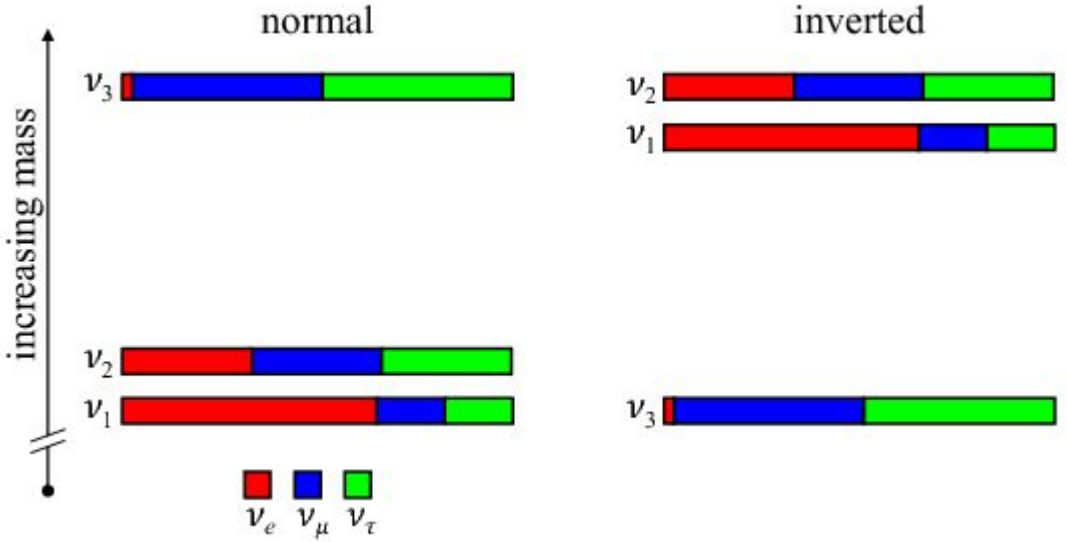
Results from NOvA:
long-baseline neutrino and antineutrino flavor oscillation

Denver Whittington, Syracuse University
On behalf of the NOvA Collaboration

WIN2019

NOvA : NuMI Off-axis ν_e Appearance

- Neutrino Mass Hierarchy
  - value and sign of the atmospheric mass splitting
- ν_3 Flavor Symmetry
- CP symmetry violation
- Other neutrinos beyond the three active flavors?



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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospheric and long baseline	reactor and long baseline	reactor and solar
$\nu_\mu \rightarrow \nu_\mu$	$\nu_e \rightarrow \nu_e$	$\nu_e \rightarrow \nu_e$
$\nu_\mu \rightarrow \nu_\tau$	$\nu_\mu \rightarrow \nu_e$	$\nu_e \rightarrow \nu_\mu + \nu_\tau$

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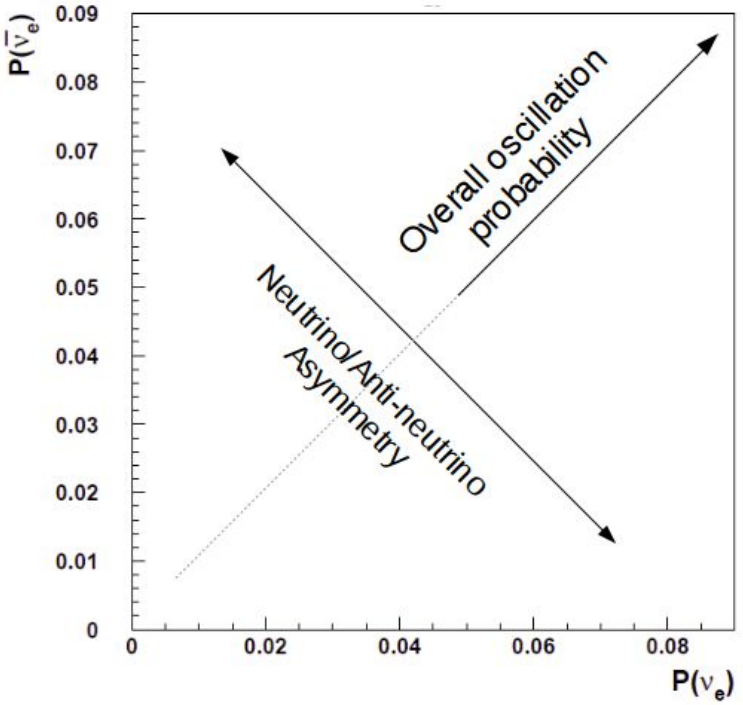

Muon neutrino and antineutrino disappearance: θ_{23} and the magnitude of Δm^2_{32}.

Electron neutrino and antineutrino appearance: ***sign*** of Δm^2_{32} and value of δ_{CP}

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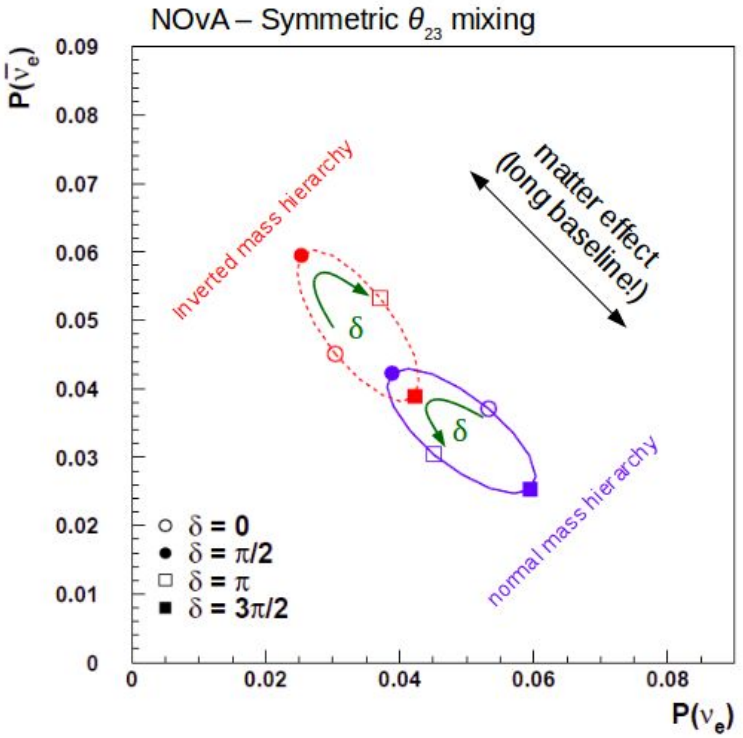

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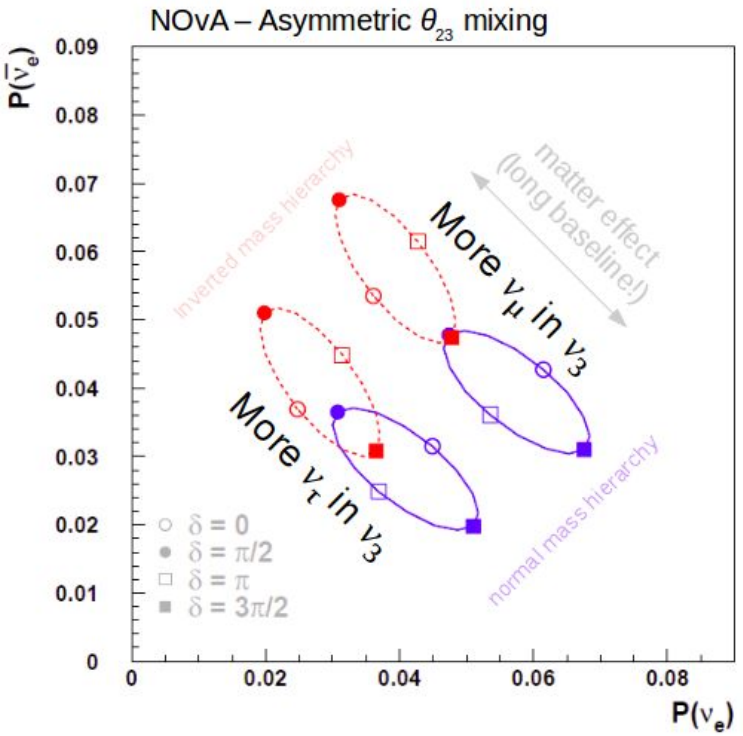
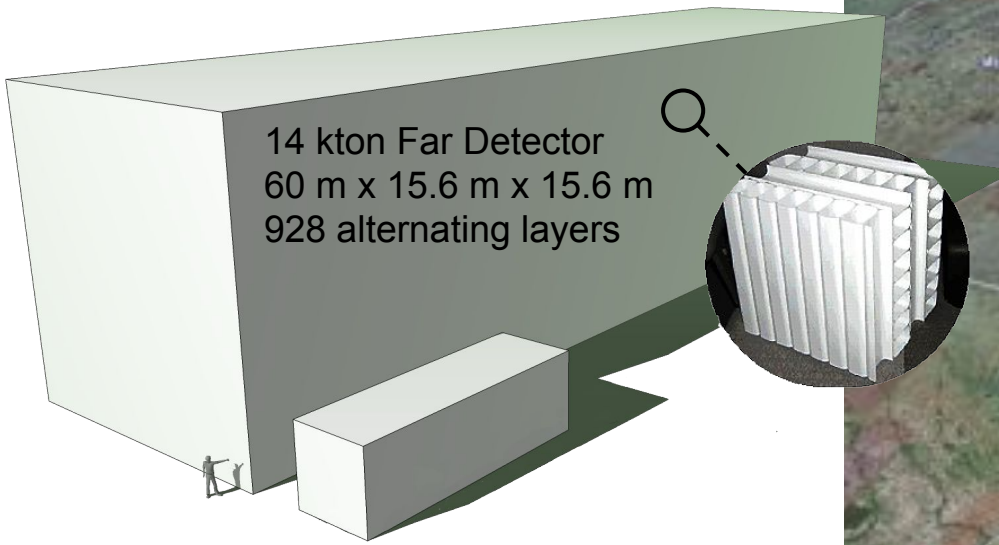


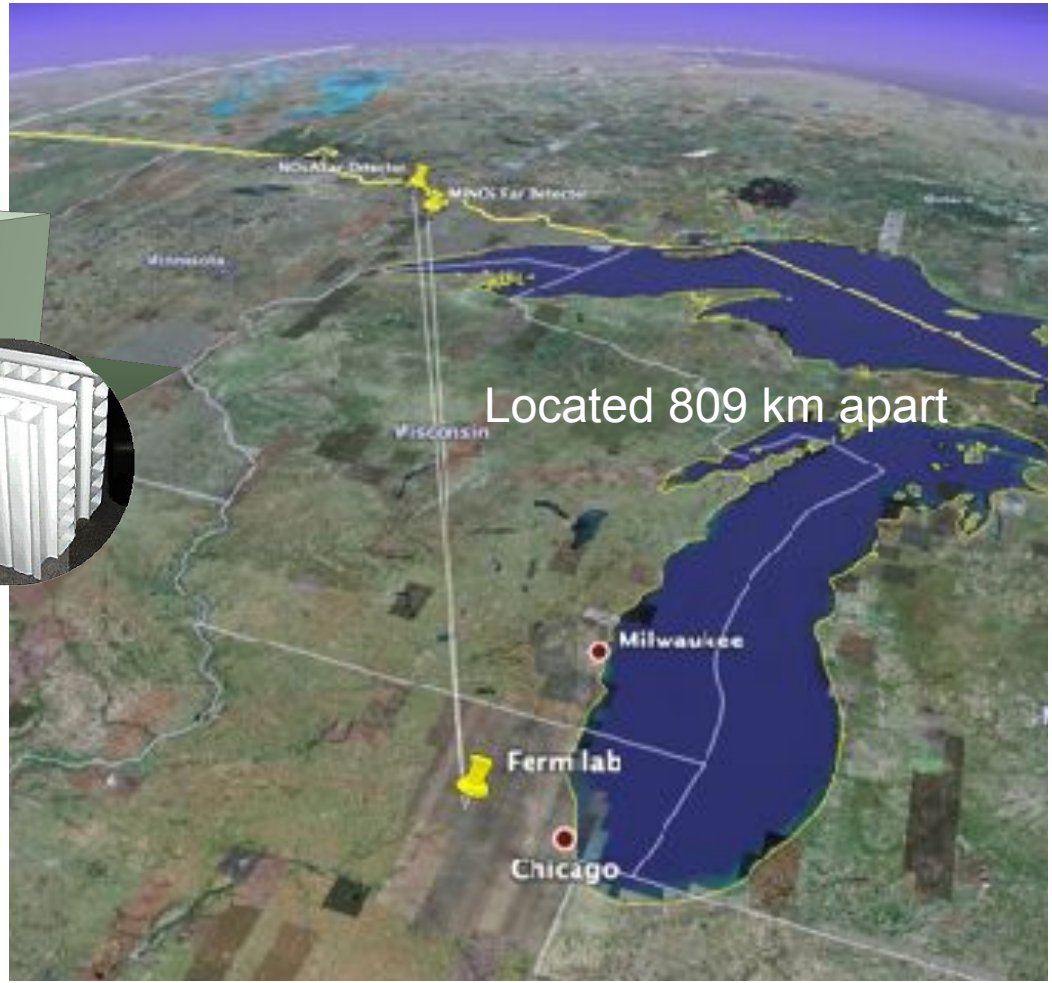
Muon neutrino and antineutrino disappearance: θ_{23} and the magnitude of Δm^2_{32}.

Electron neutrino and antineutrino appearance: ***sign*** of Δm^2_{32} and value of δ_{CP}

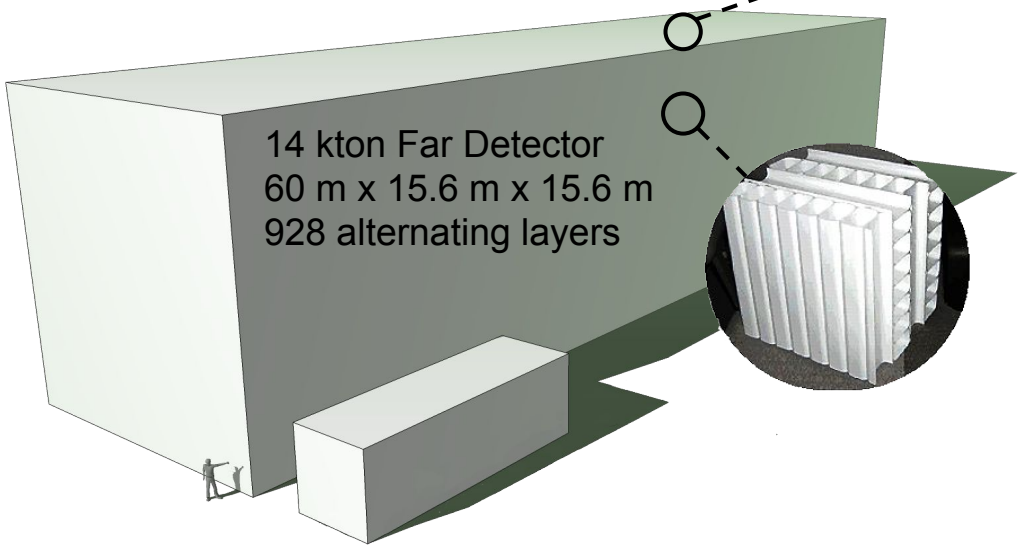
Functionally identical near and far segmented liquid scintillator detectors

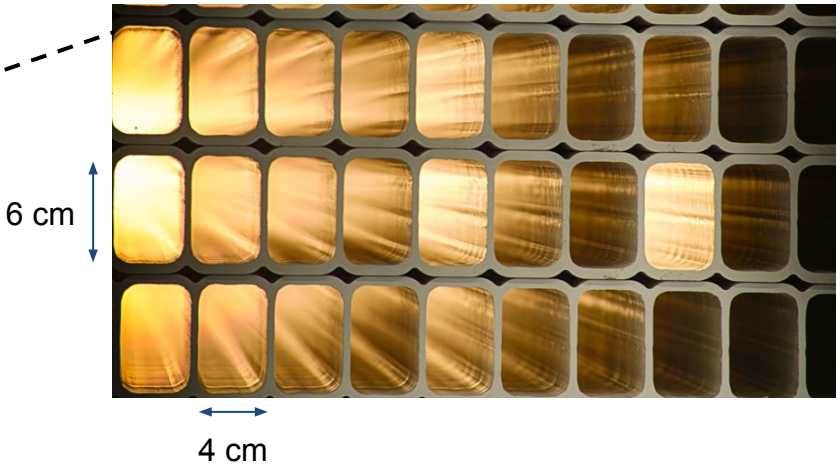


300 ton Near Detector underground at Fermilab
14.3 m x 4.1 m x 4.1 m, 206 alternating layers



Extruded PVC cells filled with 11 million liters of liquid scintillator



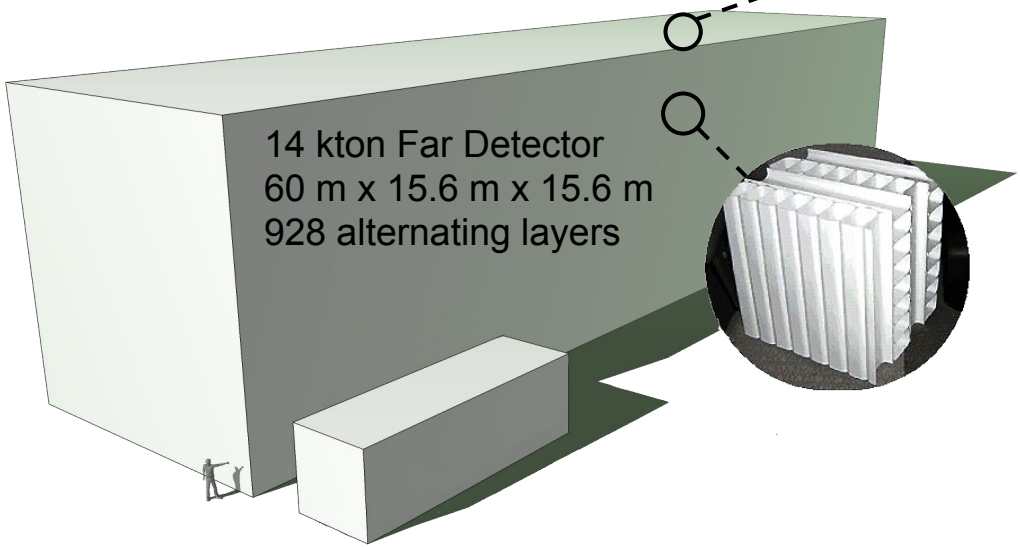


300 ton Near Detector underground at Fermilab
14.3 m x 4.1 m x 4.1 m, 206 alternating layers

Alternating layers for 3D event reconstruction

Each ~0.15 radiation lengths for e/pi separation

Extruded PVC cells filled with 11 million liters of liquid scintillator



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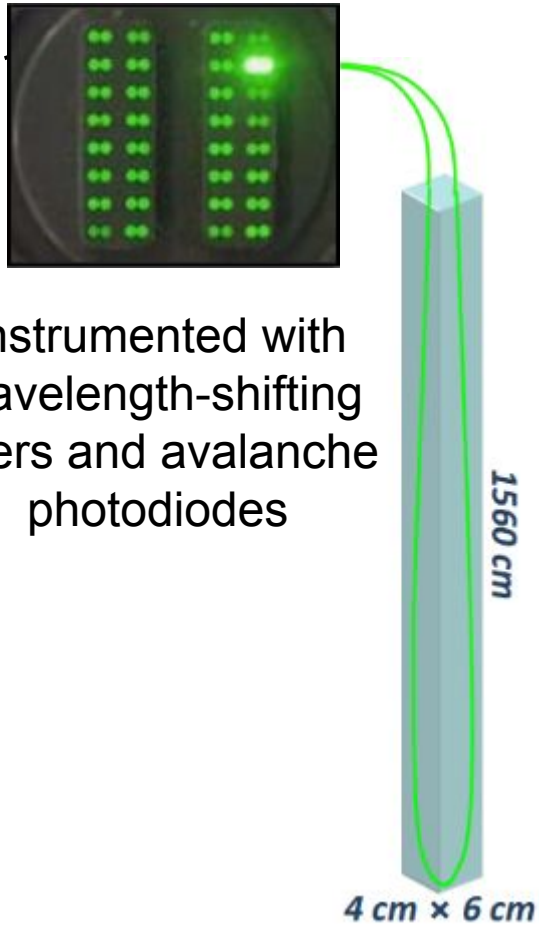
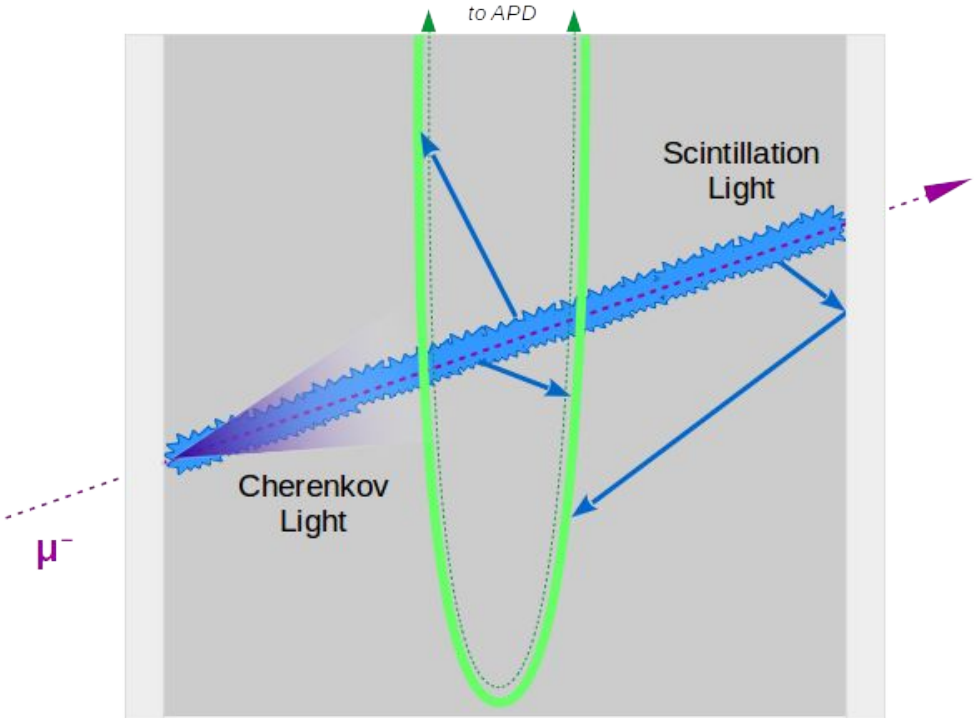
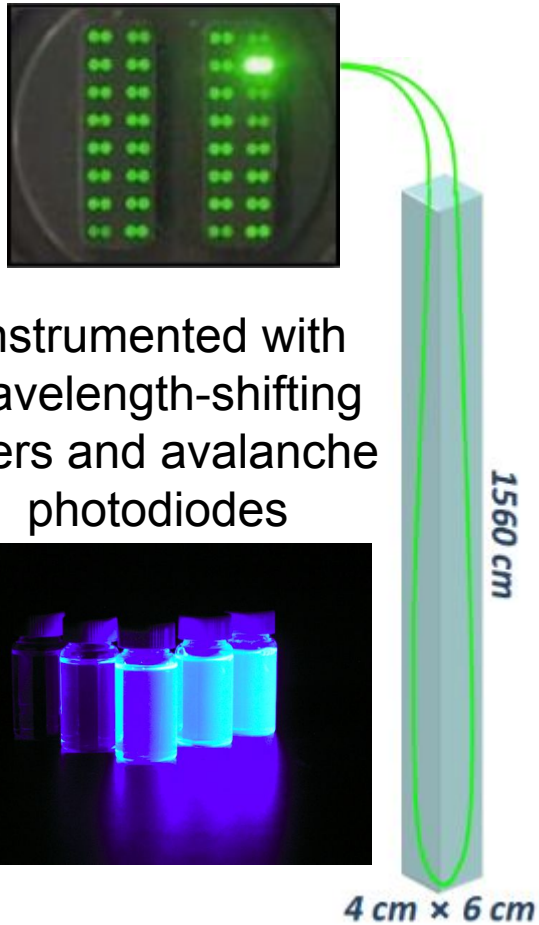


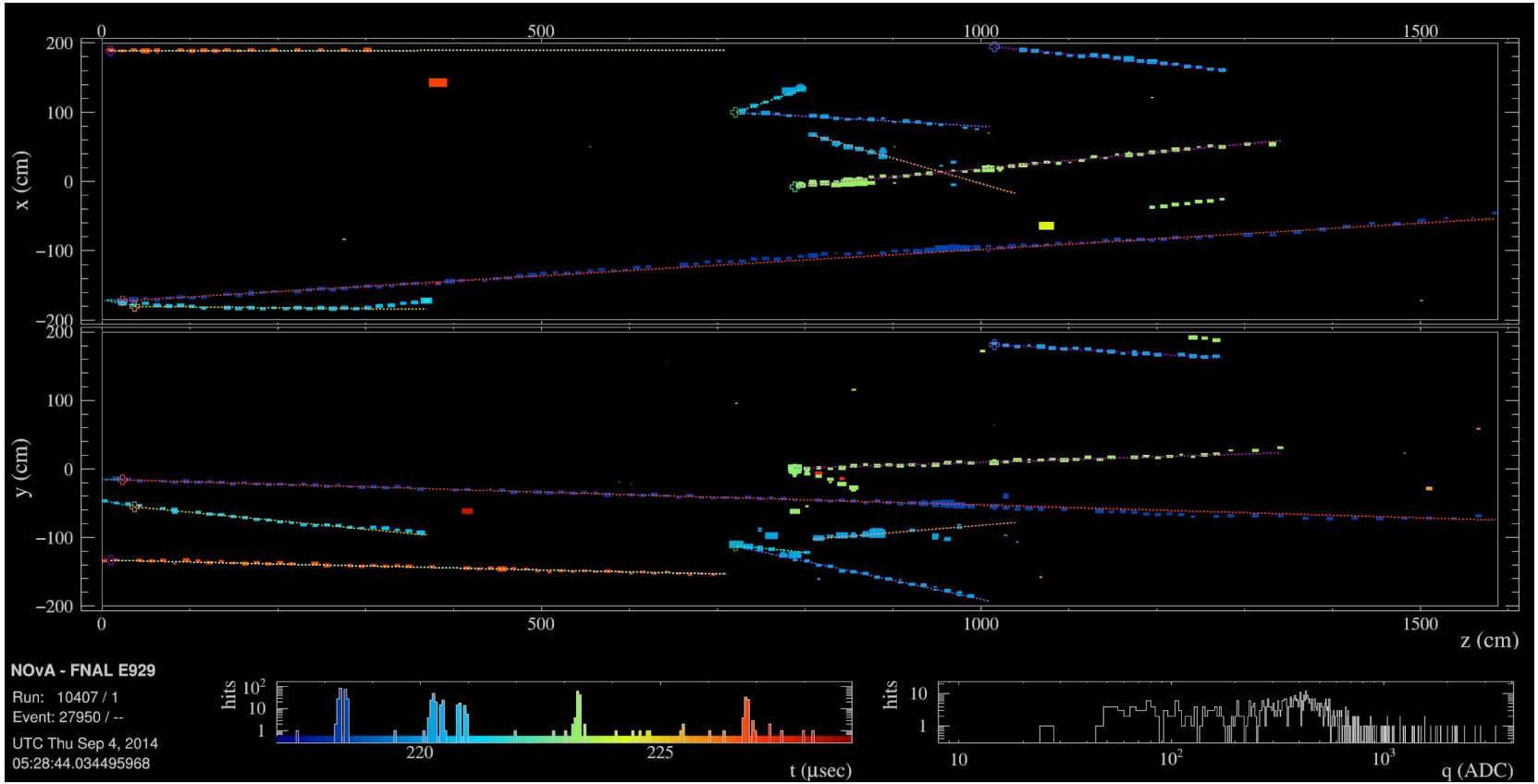
Instrumented with wavelength-shifting fibers and avalanche photodiodes

Extruded PVC cells filled with 11 million liters of liquid scintillator



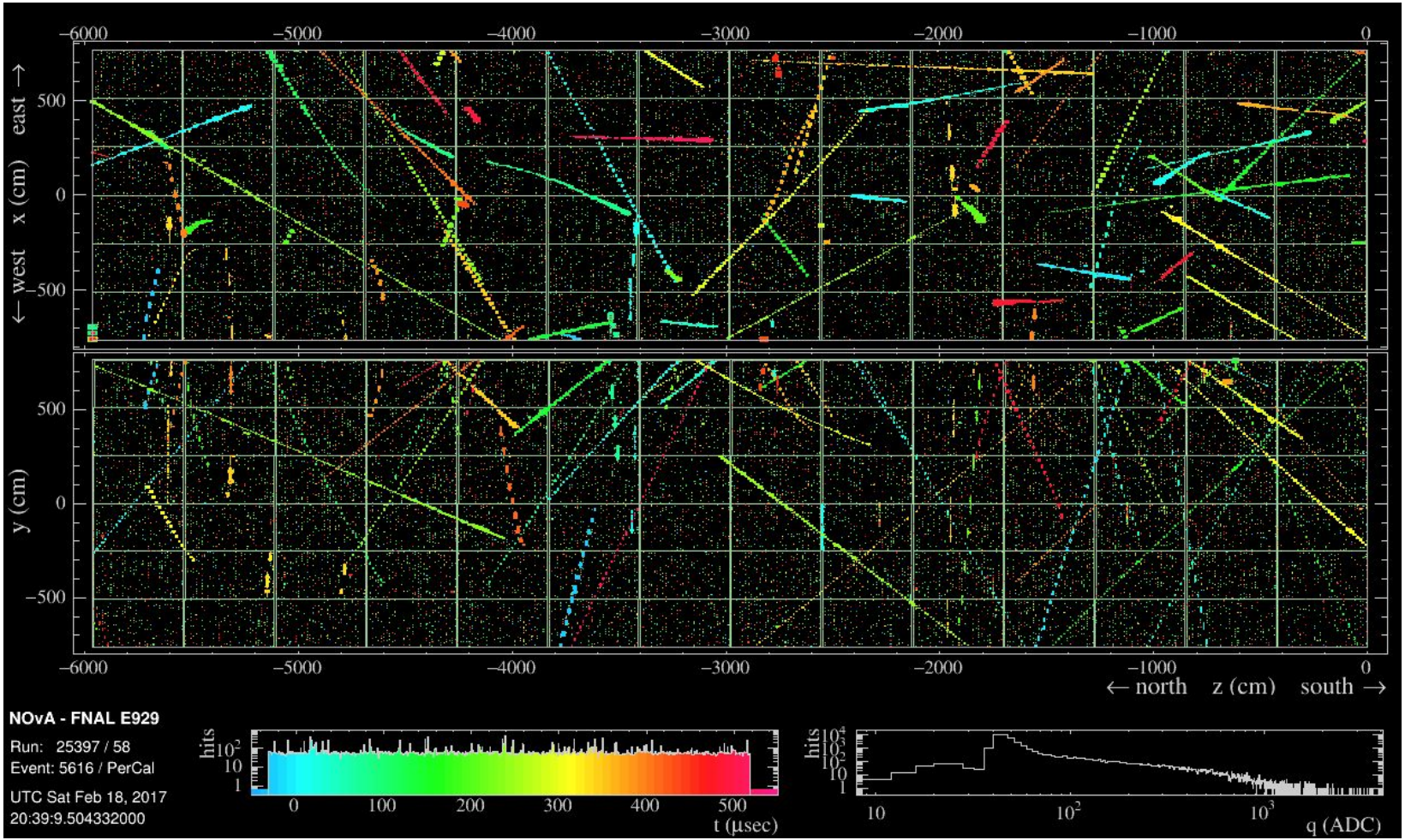


Instrumented with wavelength-shifting fibers and avalanche photodiodes

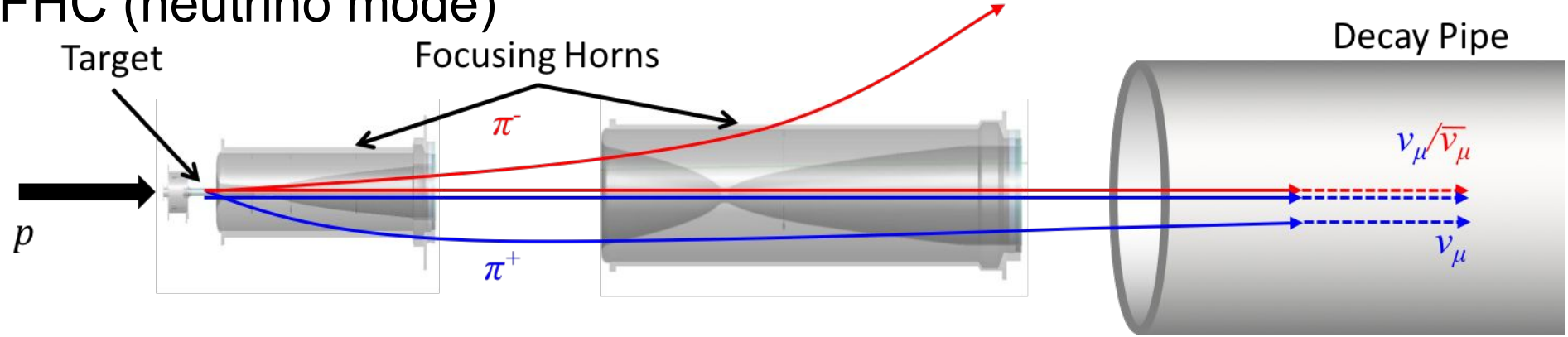

Top View
Side View
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 10407 / 1
Event: 27950 / --
UTC Thu Sep 4, 2014
05:28:44.034495968
hits
t (μsec)
q (ADC)

Top View

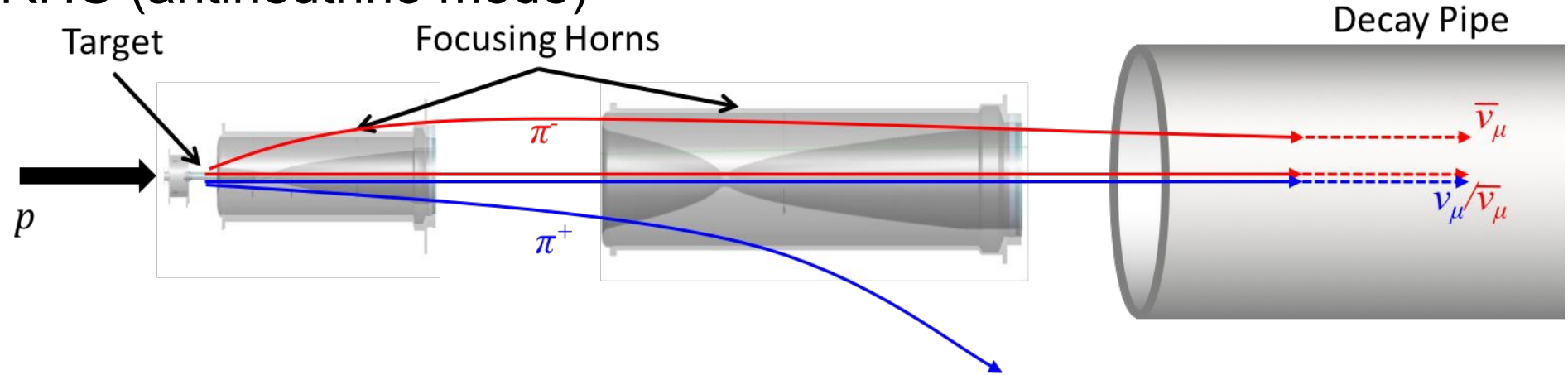
Side View



FHC (neutrino mode)

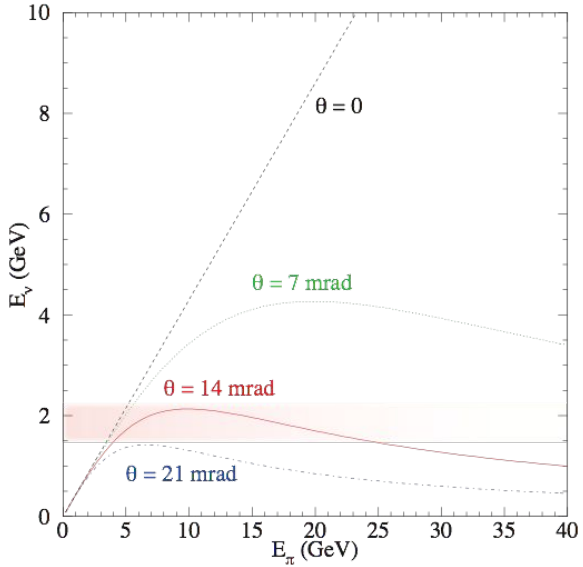


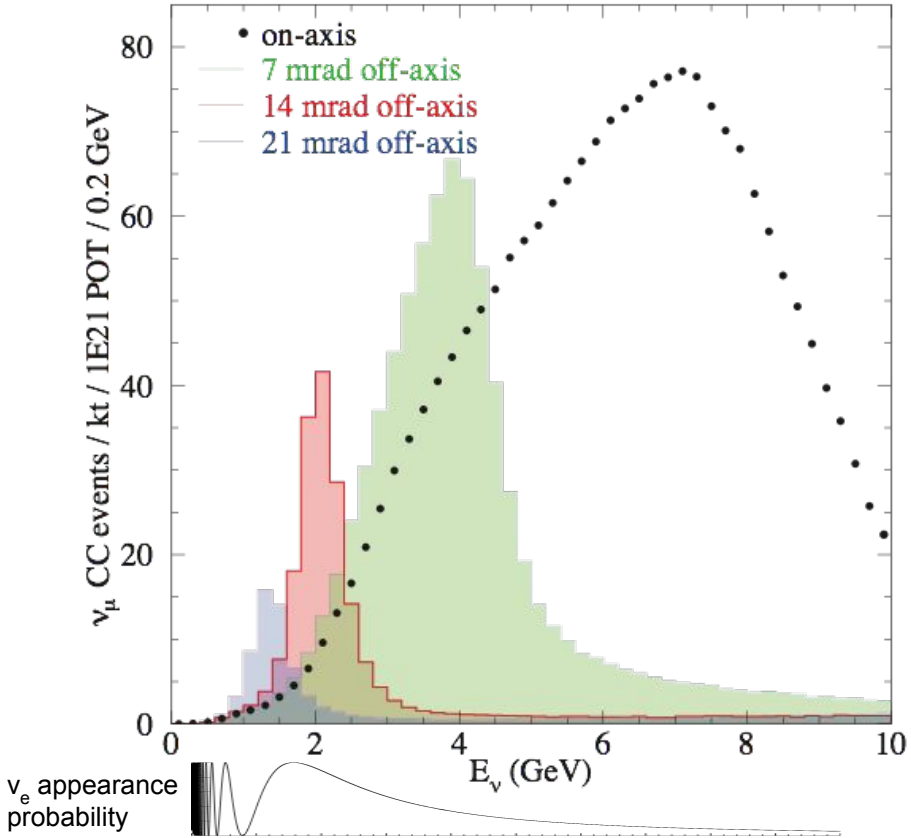
RHC (antineutrino mode)



NuMI Off-Axis → nearly monoenergetic neutrino beam

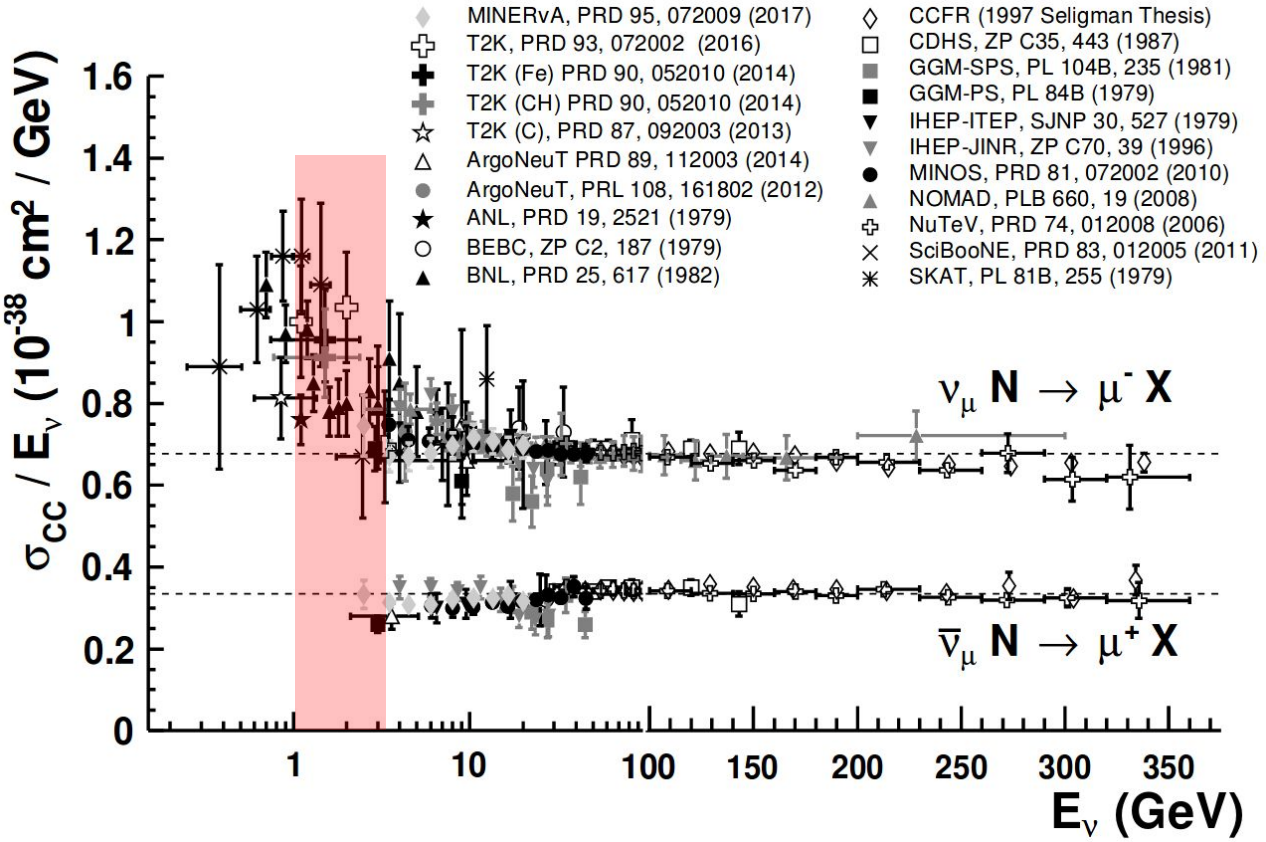
$\pi \rightarrow \nu_\mu + \mu$ back-to-back in COM frame
boosted to the lab frame



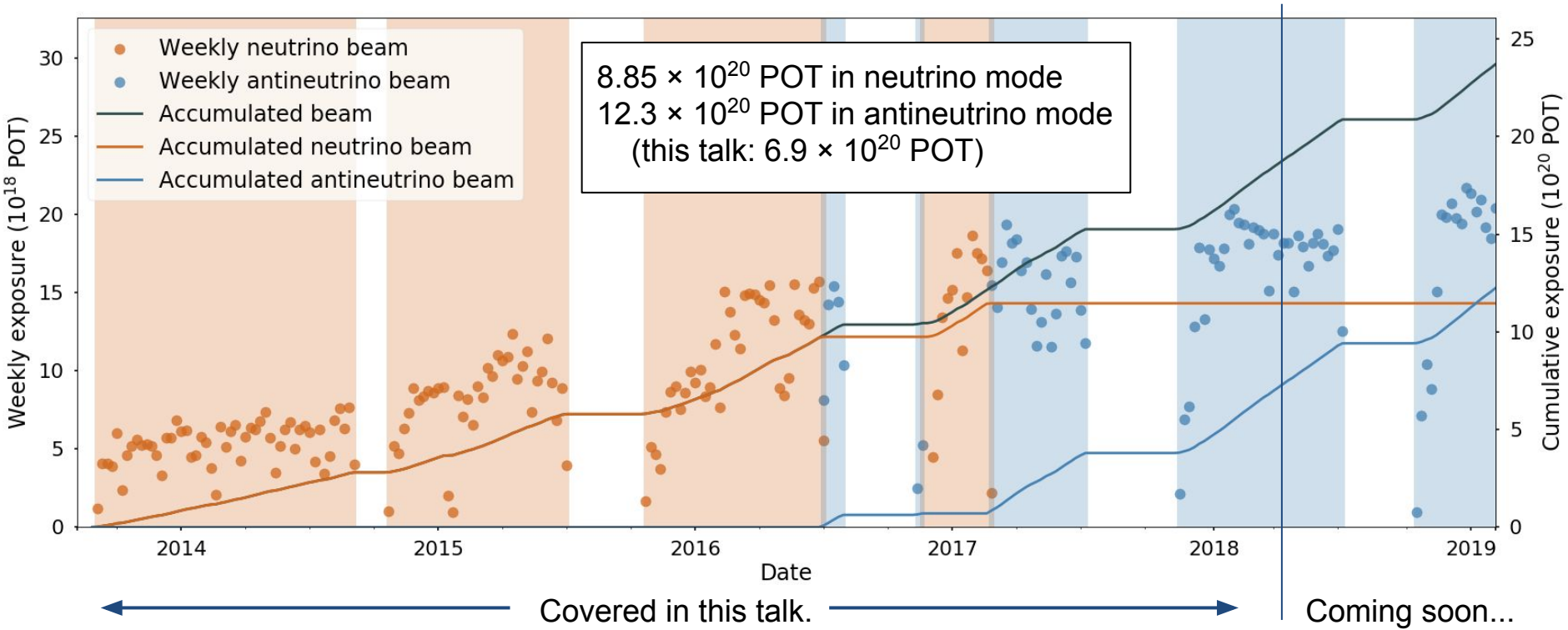


NOvA is exploring neutrino interactions at an important low-energy region.

- High-statistics data from NOvA near detector
- Combination of quasi-elastic, resonance, and more complicated interactions
- Overlap with MiniBooNE, T2K, & MINERvA measurements
- DUNE 1st oscillation maximum
- Measurements of both neutrino and antineutrino interactions



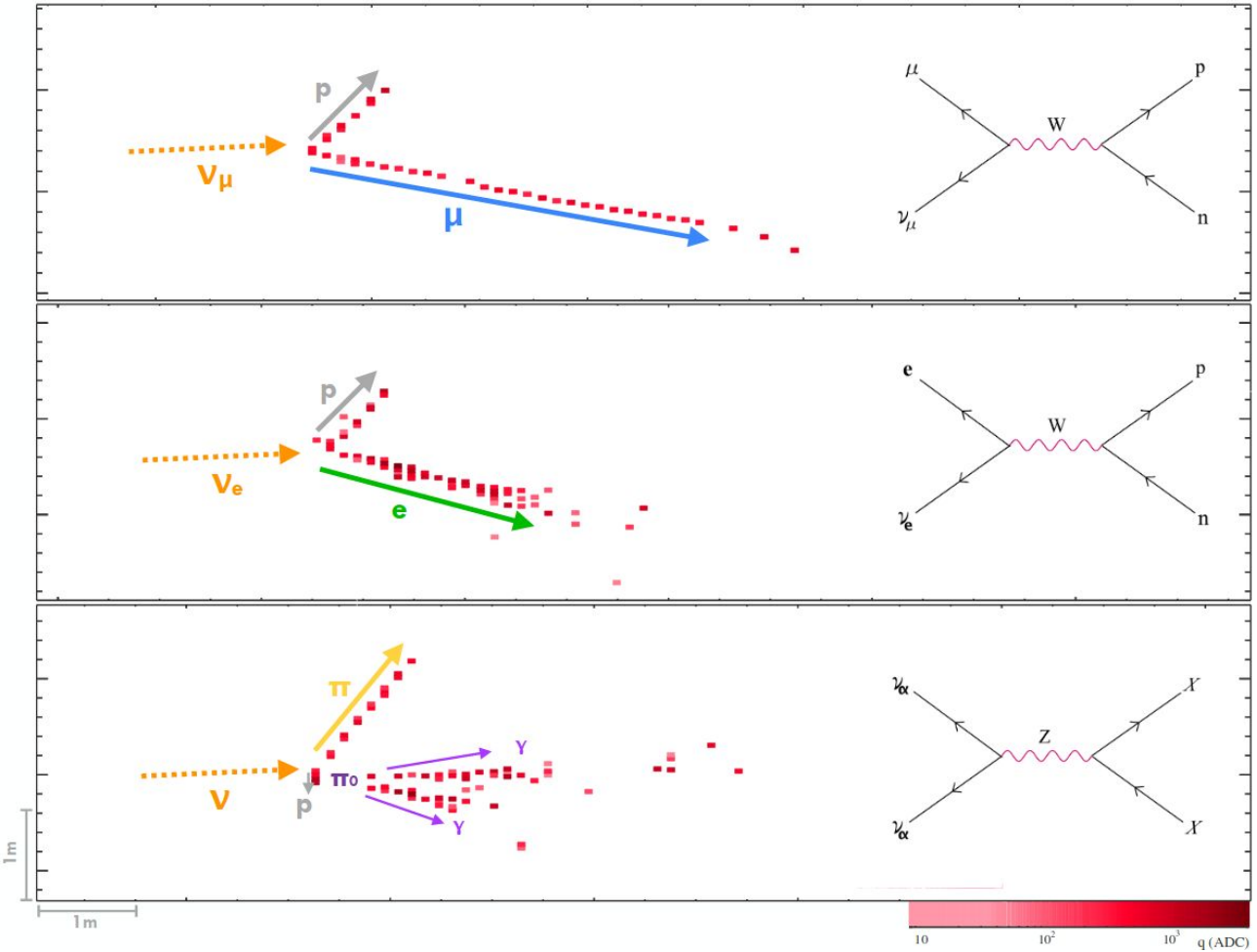
The NOvA neutrino dataset keeps growing.



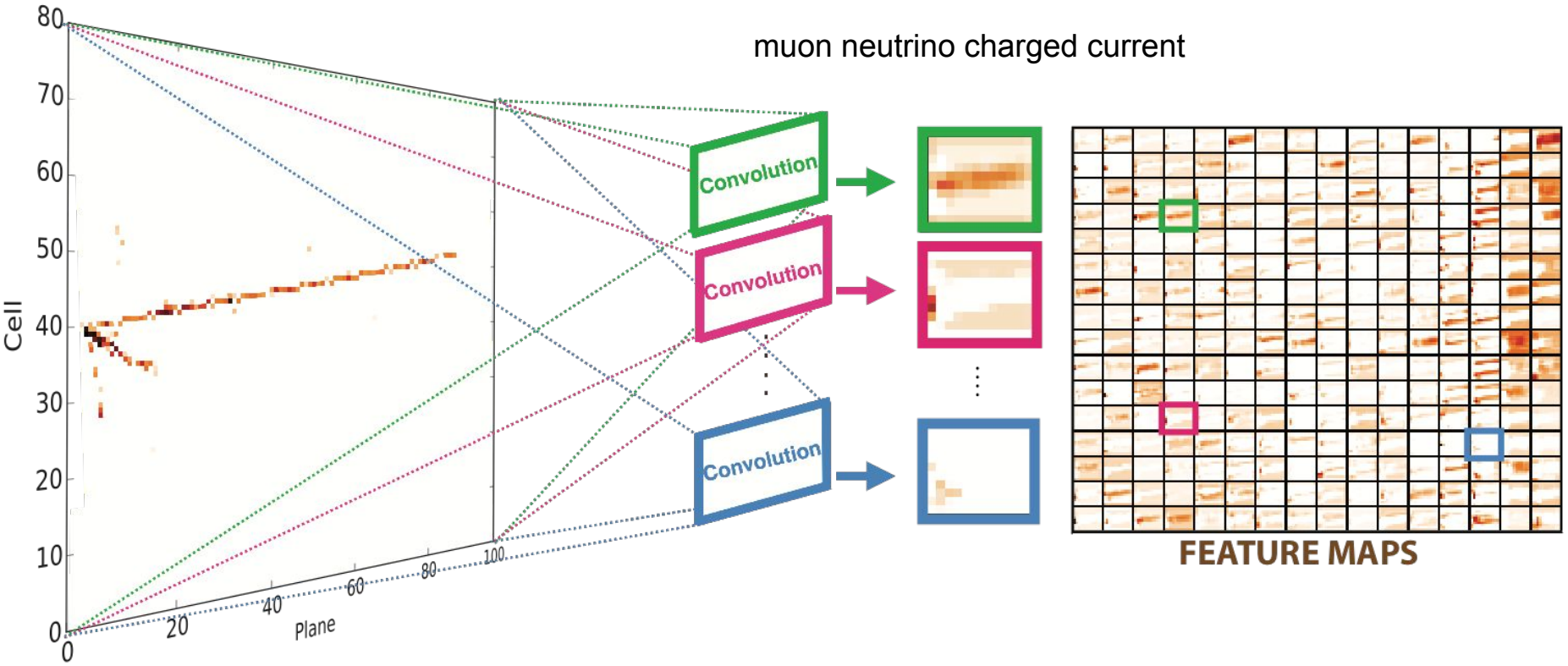
Many thanks go to Fermilab for this amazing neutrino beam!

Inside Neutrino Events

- Identify components
  - tracks, showers, vertex, hadronic activity
- Measure properties
  - dE/dx, momenta, calibrated energy
- Reject cosmic rays and associated activity
  - muons, neutrons, etc.
- Identify the event type
  - Distinguish between CC and NC events
  - Electron, muon, or tau neutrino
  - Quasi-elastic, resonant, deep inelastic, etc.



Events are classified using a Convolutional Neural Network



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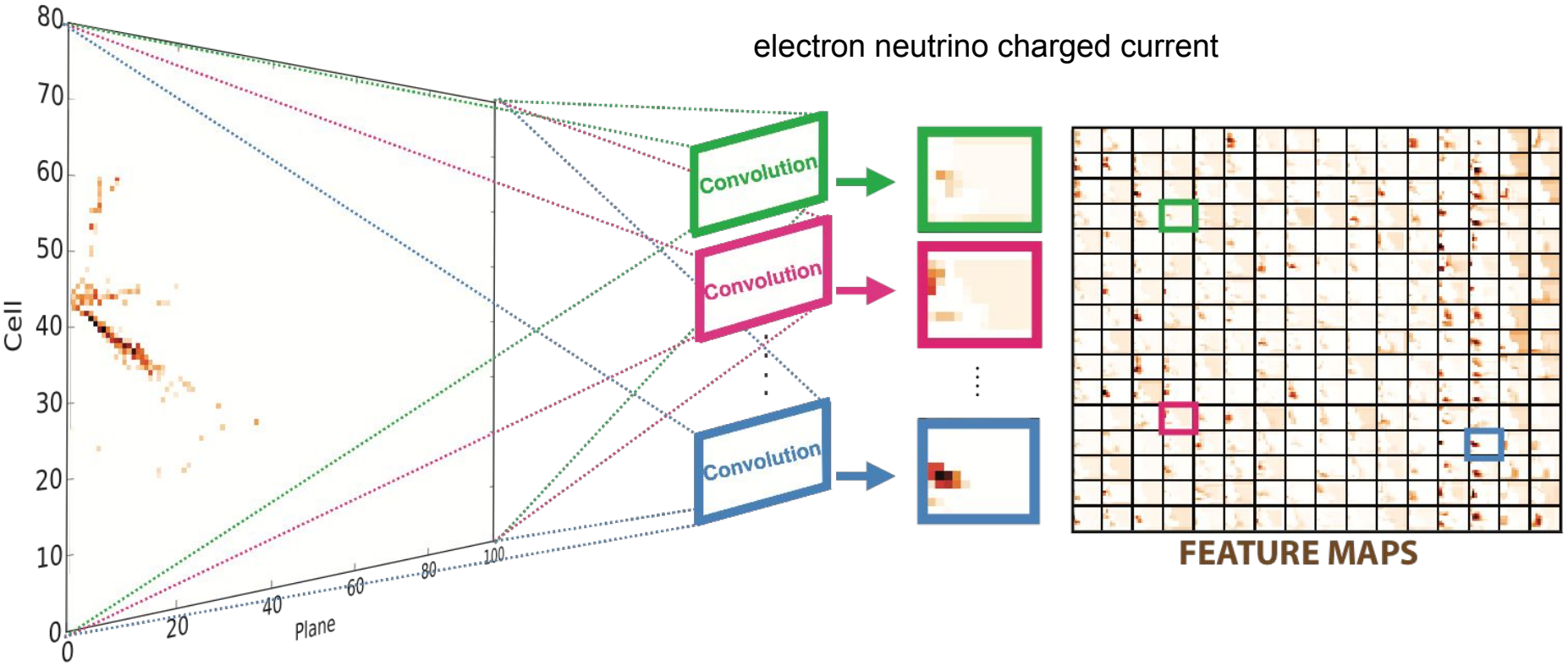

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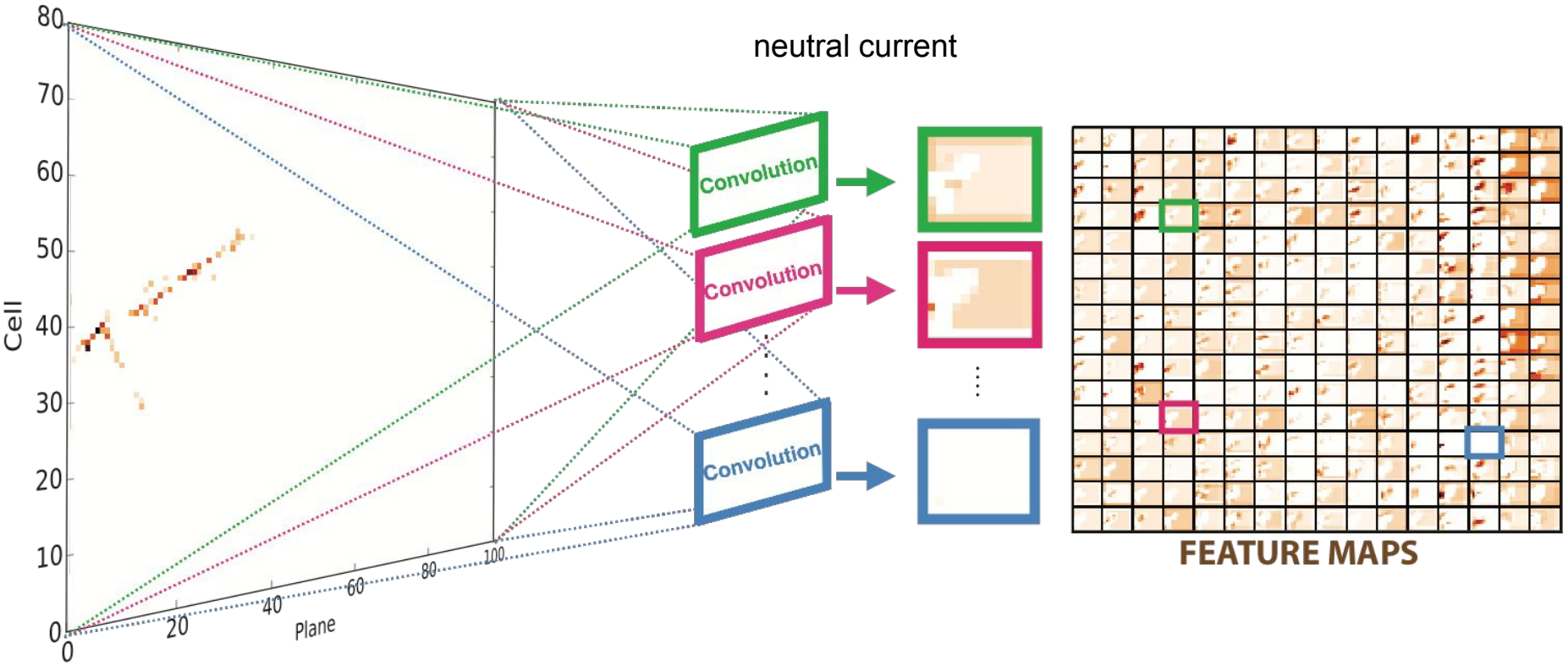
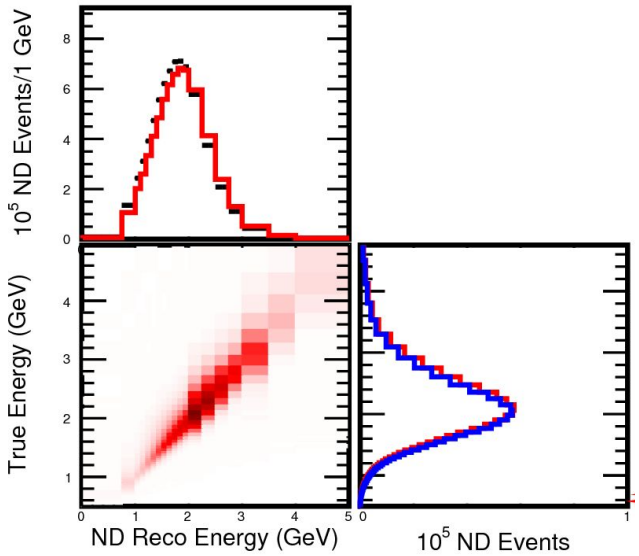
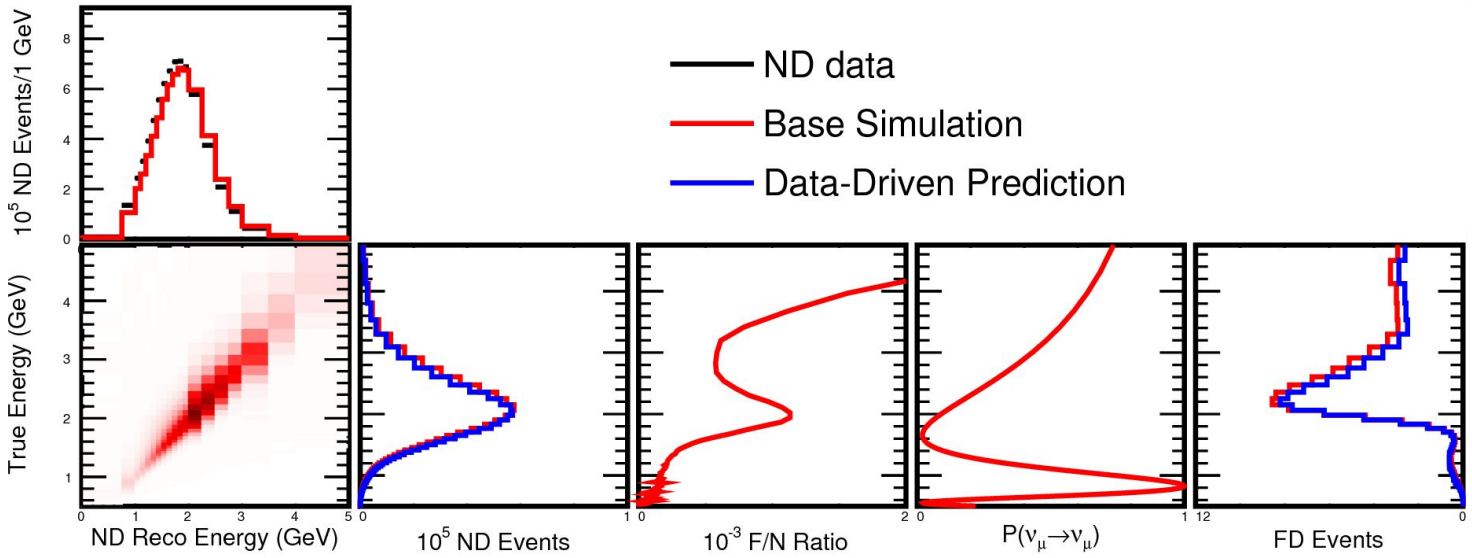




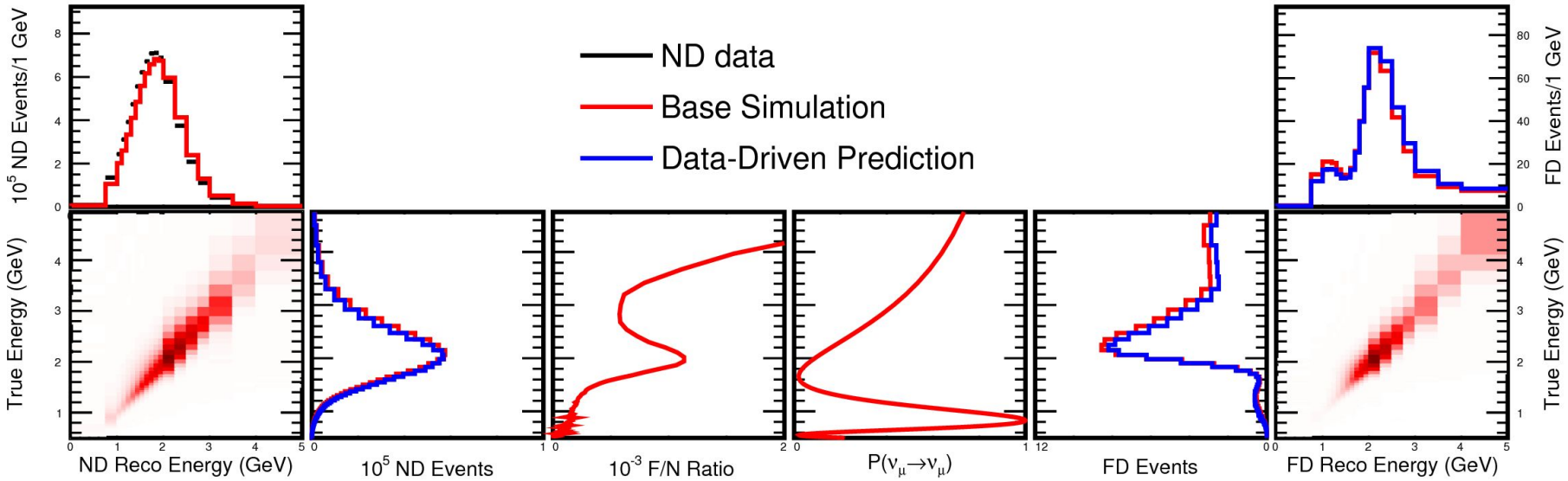
ND data
Base Simulation
Data-Driven Prediction

Data-Driven Prediction:
Reweight the underlying simulated neutrino energy spectrum using high-statistics near detector data.

Sample the neutrino spectrum in the event selection at the near detector and extrapolate to predict the spectrum at the far detector...



Multiply by the far-to-near flux ratio (shape of beam at far vs near detectors) and the oscillation probability to predict the true spectrum at the far detector.

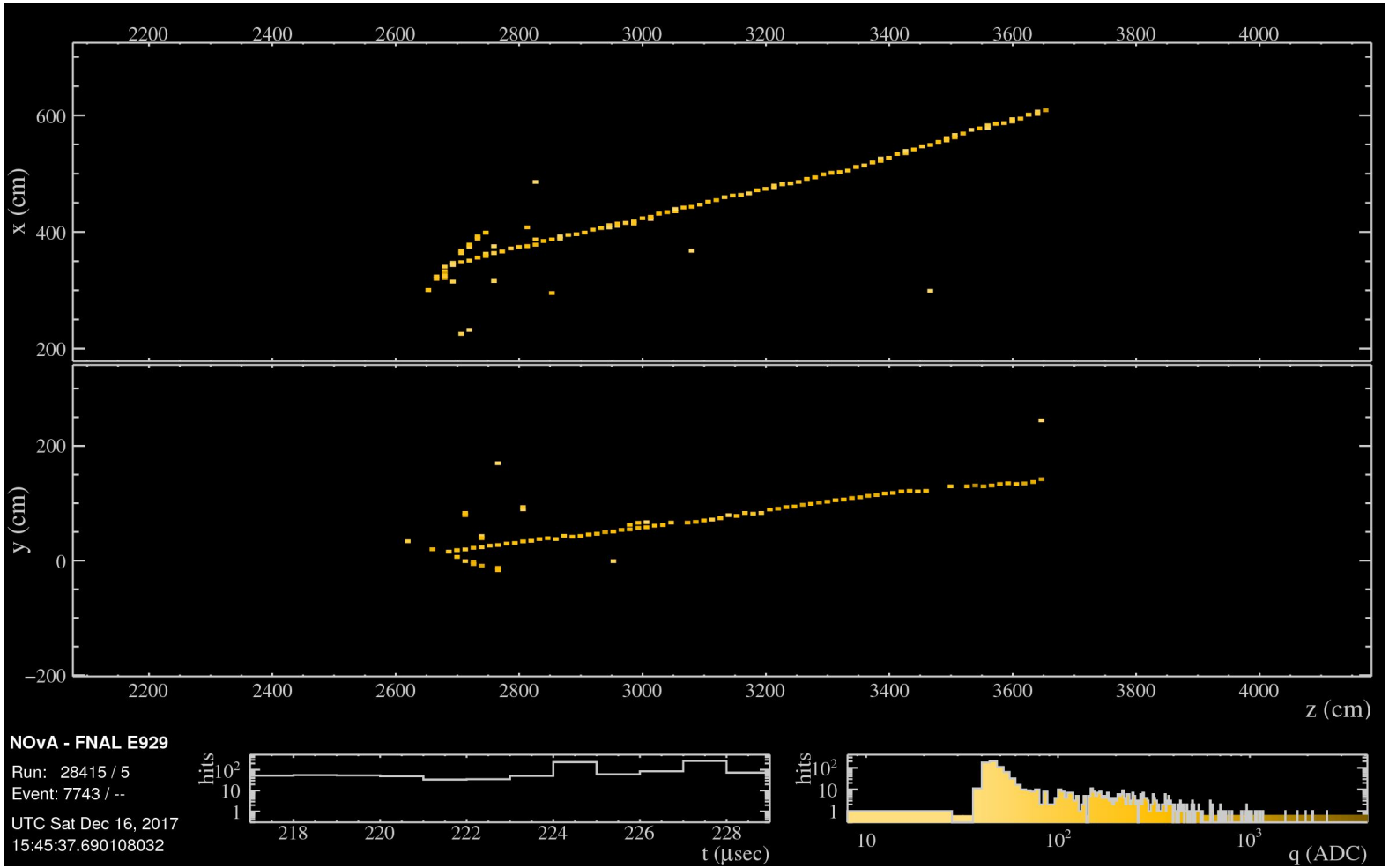


Convert back to reconstructed energy to compare to far detector data.

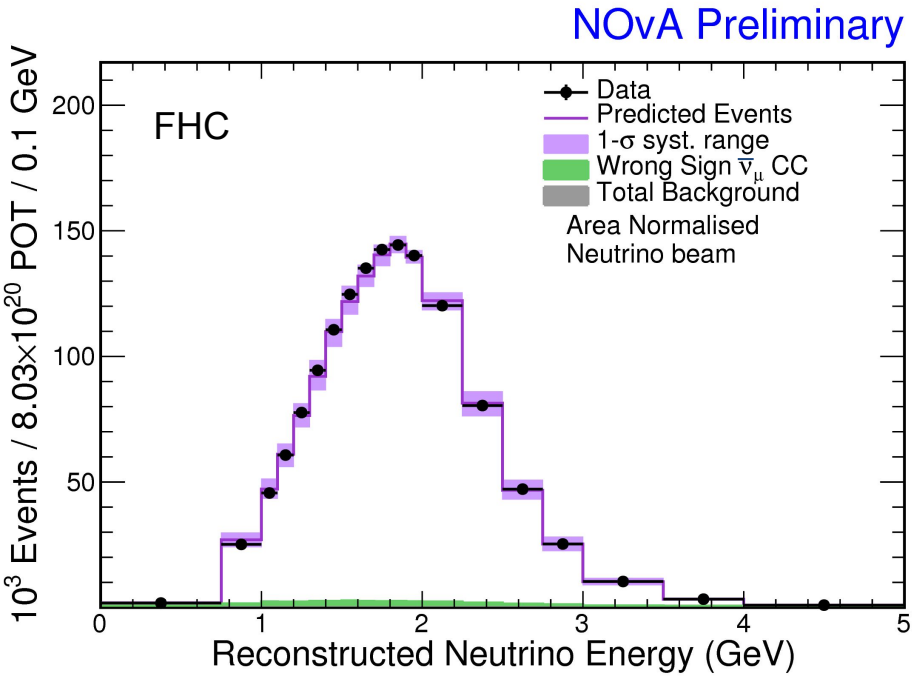
Leverage correlations in systematics between near & far detectors to better constrain the prediction at the far detector.

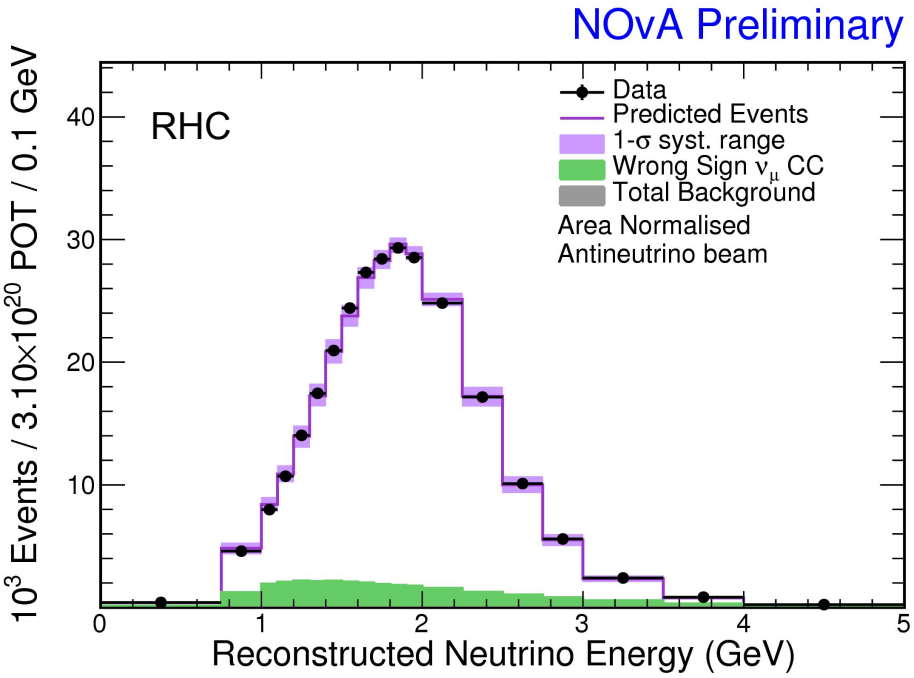
$$N_{near}(E_\nu^{reco}) = \Phi(E_\nu^{true}) \times \sigma(E_\nu^{true}, A) \times R(E_\nu^{true}) \times \epsilon(...)$$

$$N_{far}(E_\nu^{reco}) = P_{osc}(E_\nu^{true}) \times \Phi(E_\nu^{true}) \times \sigma(E_\nu^{true}, A) \times R(E_\nu^{true}) \times \epsilon(...)$$

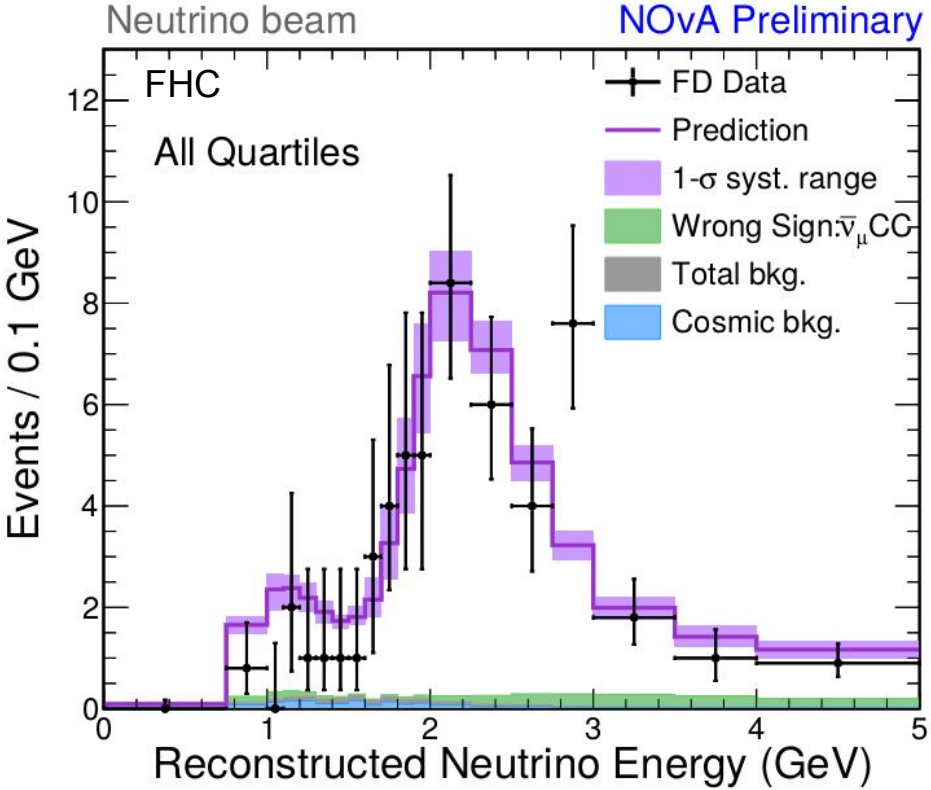

2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
600
400
200
x (cm)
200
0
−200
y (cm)
z (cm)
NOvA - FNAL E929
Run: 28415 / 5
Event: 7743 / --
UTC Sat Dec 16, 2017
15:45:37.690108032
hits
10^2
10
1
218
220
222
224
226
228
t (µsec)
hits
10^2
10
1
10
10^2
10^3
q (ADC)

Measured and simulated neutrino spectra at the NOvA Near Detector

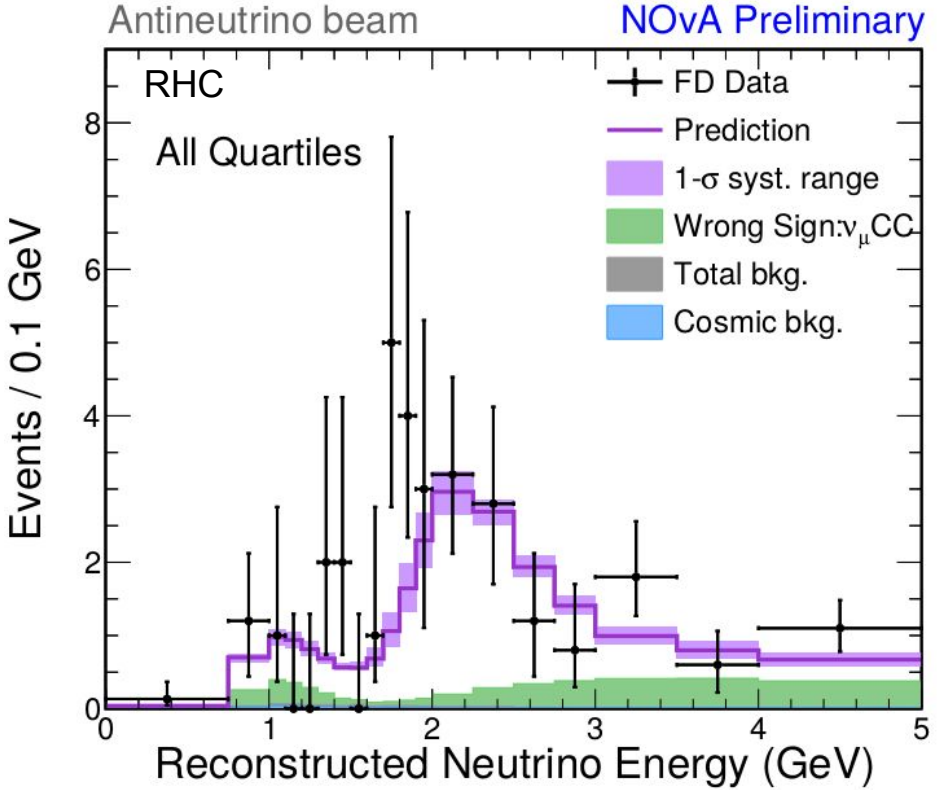




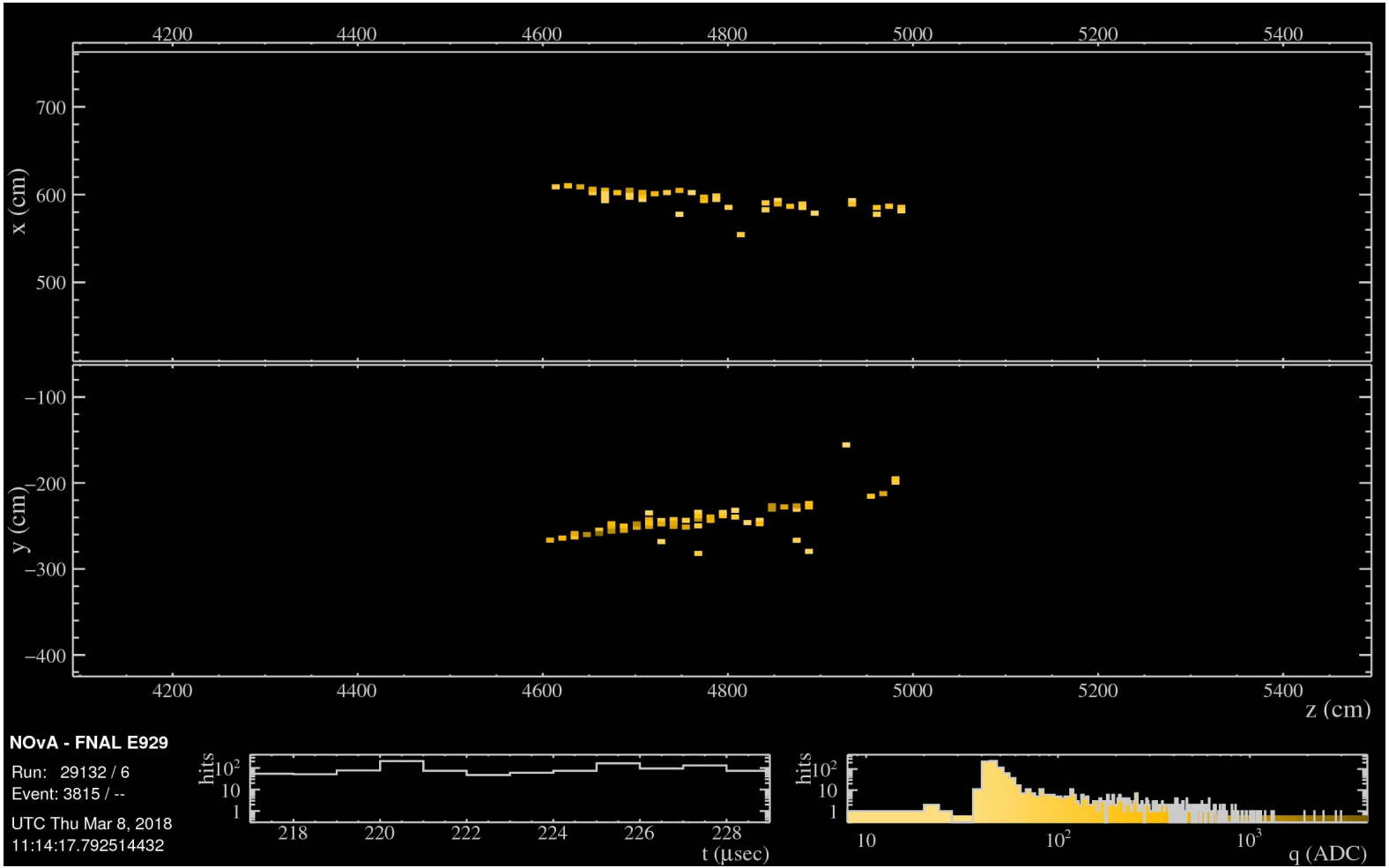
Predicted and measured neutrino spectra at the NOvA Far Detector



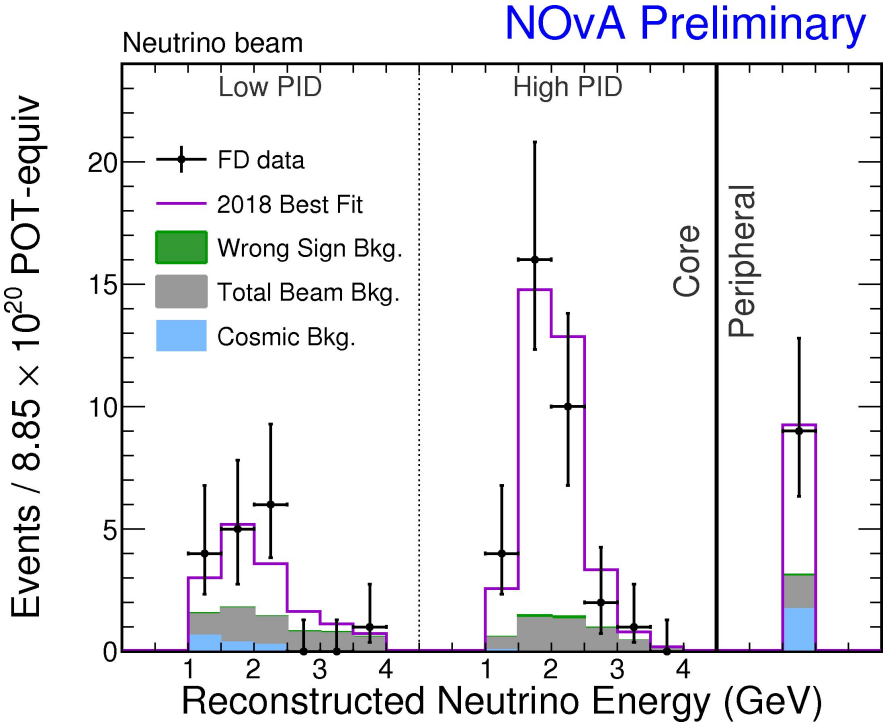
Observe 113 events (expect 730 w/o oscillations)



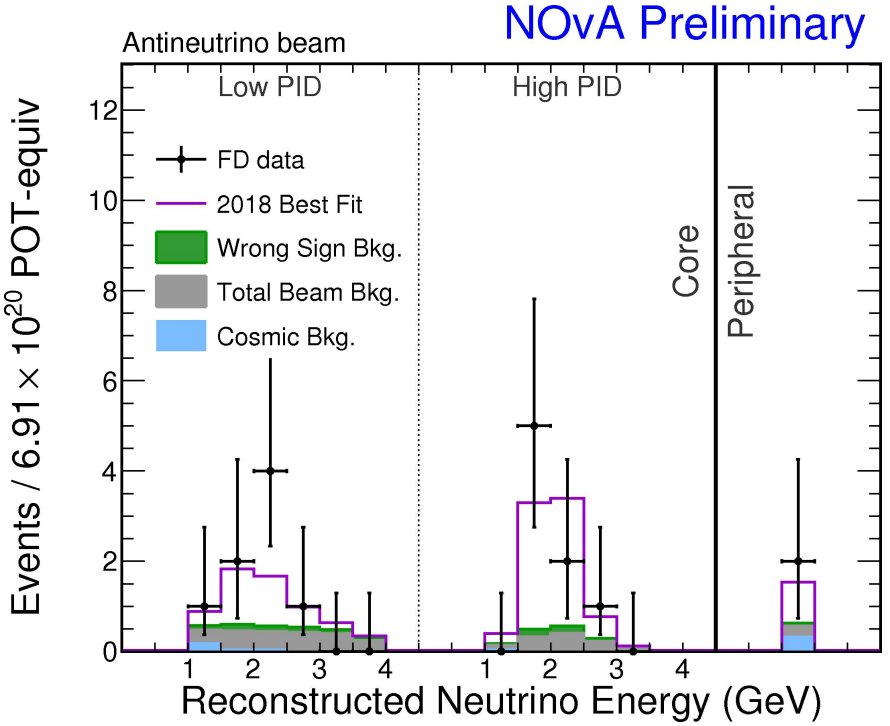
Observe 65 events (expect 266 w/o oscillations)


4200
4400
4600
4800
5000
5200
5400
700
600
500
x (cm)
−100
−200
−300
−400
y (cm)
z (cm)
NOvA - FNAL E929
Run: 29132 / 6
Event: 3815 / --
UTC Thu Mar 8, 2018
11:14:17.792514432
hits
10^2
10
1
218
220
222
224
226
228
t (μsec)
hits
10^2
10
1
10
10^2
10^3
q (ADC)

Neutrino beam (FHC): We observe 58 events and expect 15 background interactions
11 beam, 3 cosmics, and < 1 antineutrino



Antineutrino beam (RHC): We observe 18 events and expect 5.3 background interactions
3.5 beam, < 1 cosmic, and 1 neutrino



> 4σ evidence of electron antineutrino appearance!

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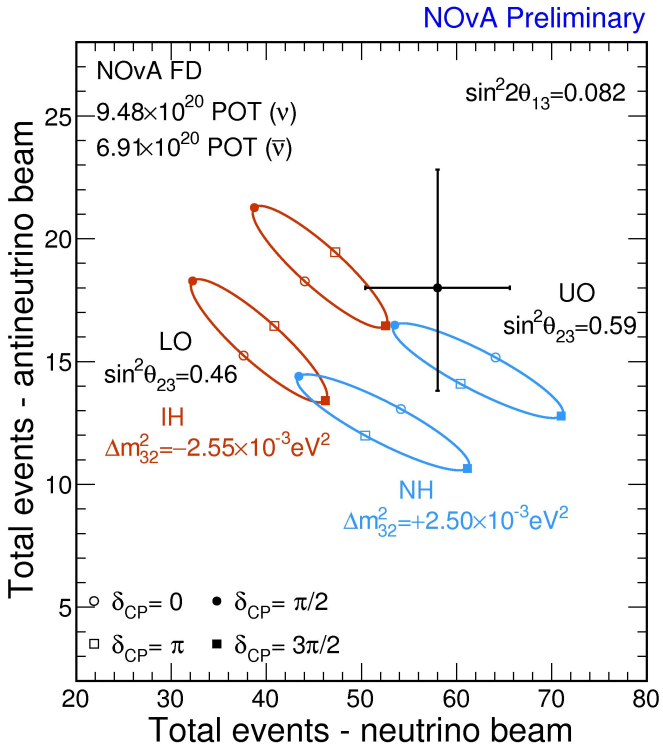
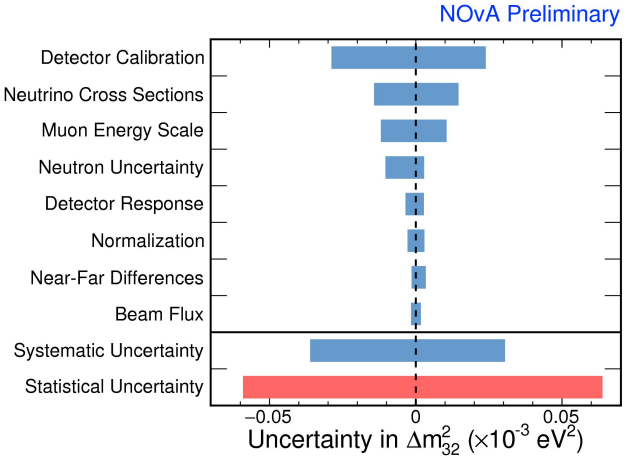
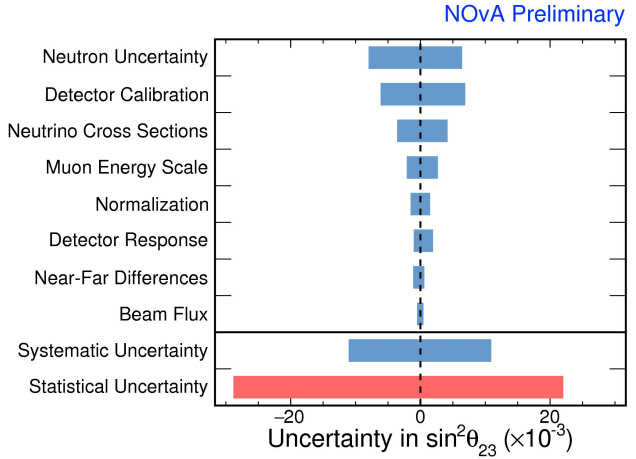


Muon neutrino and antineutrino disappearance: θ_{23} and the magnitude of Δm^2_{32}.

Electron neutrino and antineutrino appearance: ***sign*** of Δm^2_{32} and value of δ_{CP}

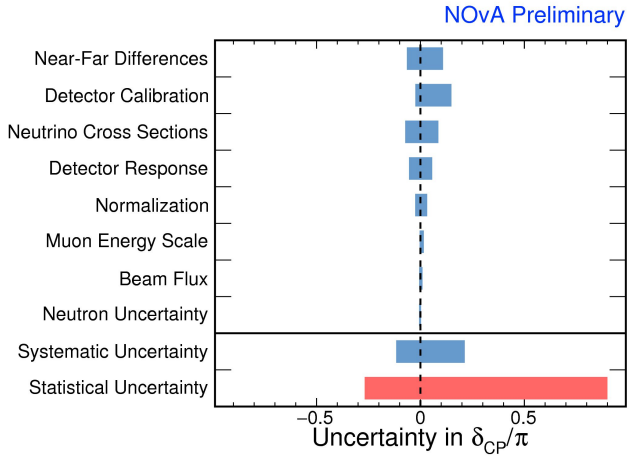
NOvA is still statistics-limited in this analysis, but data taking continues.

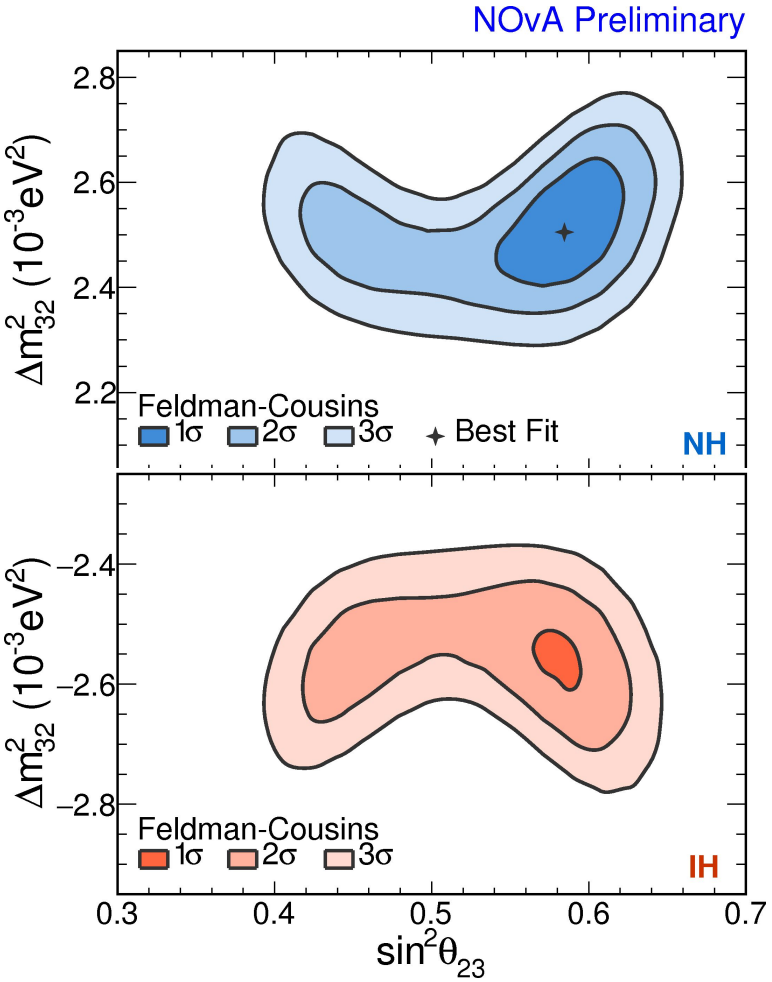




The leading systematics are detector calibration, neutrino/antineutrino cross section uncertainties, and contributions from neutron response.

Our upcoming testbeam program will address many of these contributions.



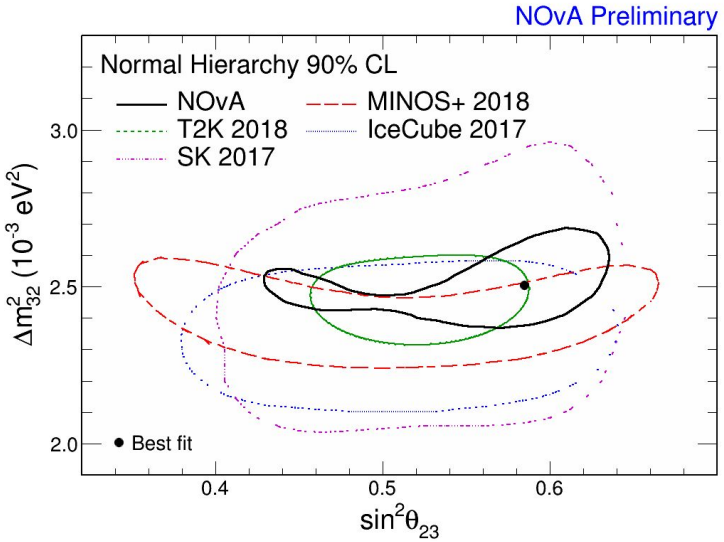


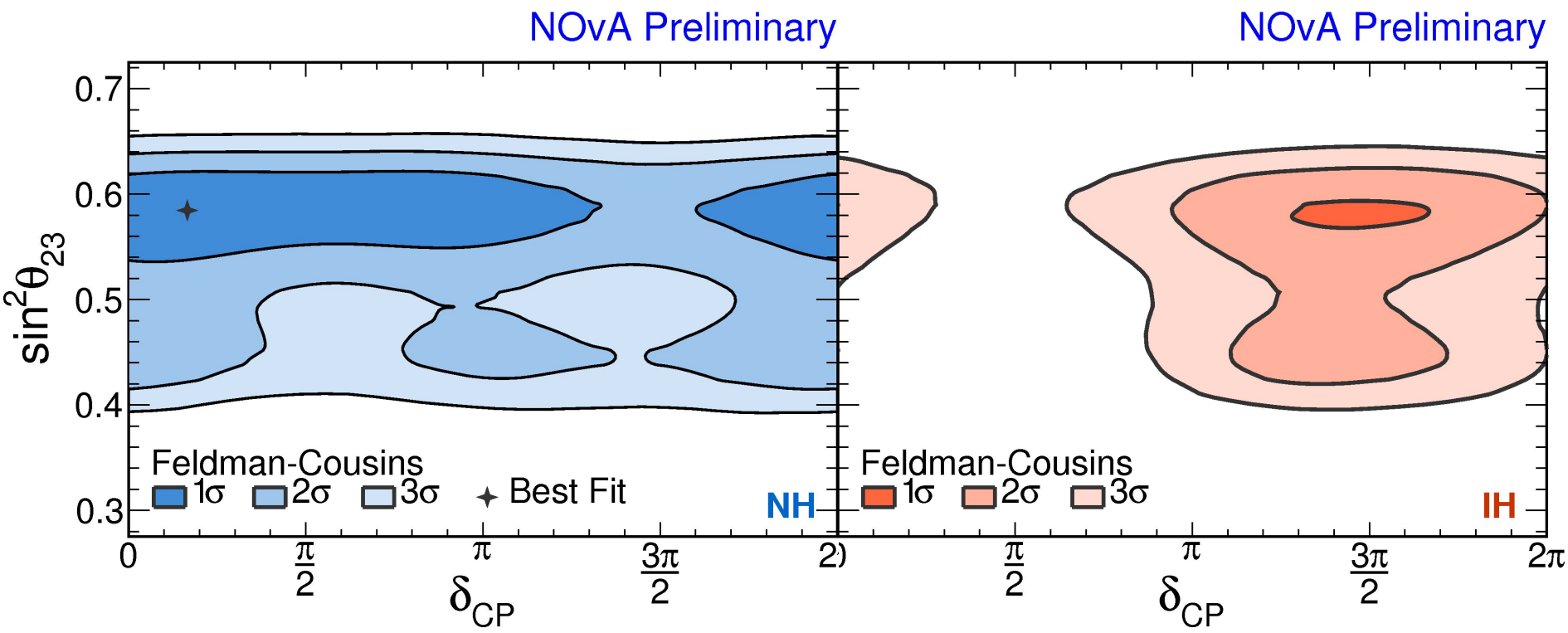
Best Fit Point: Normal Hierarchy

$\sin^2\theta_{23} = 0.58 \pm 0.03$ (Upper Octant)

$\Delta m^2_{32} = (2.51\ ^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2

Prefer non-maximal mixing at 1.8σ
(exclude LO at similar level)



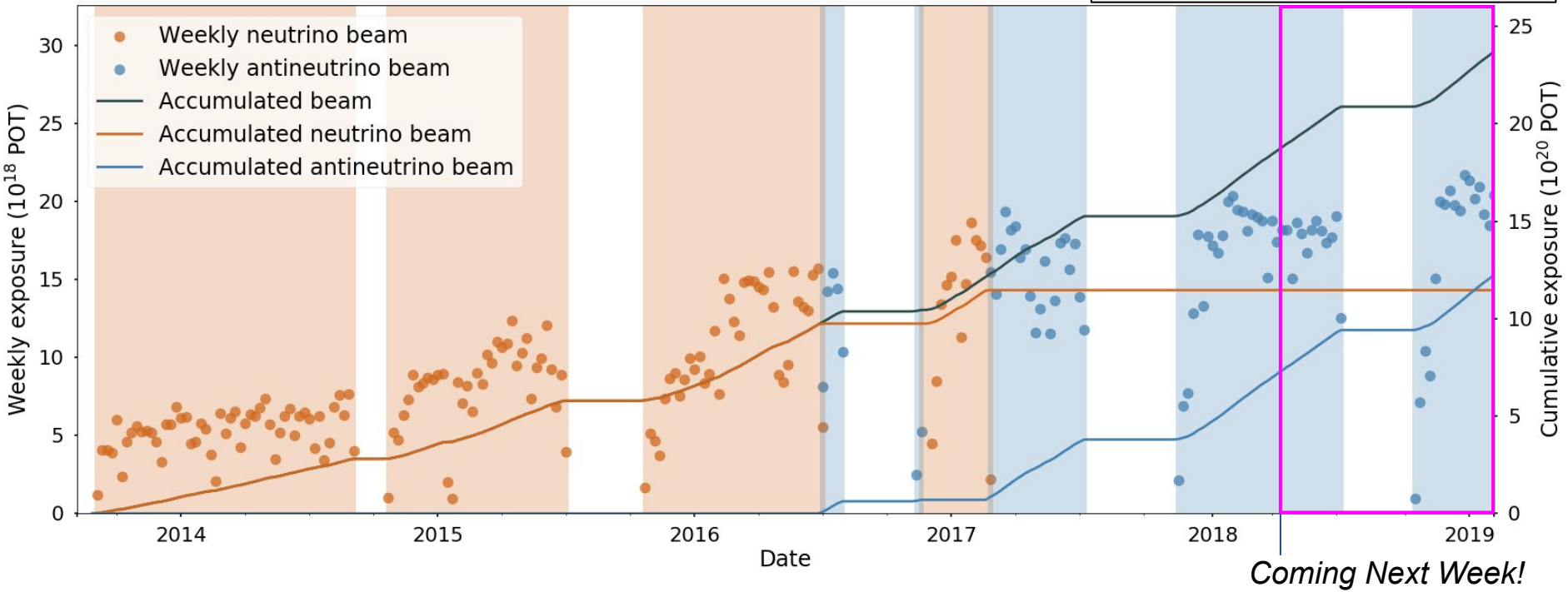


Best Fit Point: Normal Hierarchy, $\delta_{CP} = 0.17\ \pi$
$\sin^2\theta_{23} = 0.58 \pm 0.03$ (Upper Octant), $\Delta m^2_{32} = (2.51\ ^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2

Prefer Normal Hierarchy by 1.8σ | Exclude $\delta_{CP} = \pi/2$ in Inverted Hierarchy at >3σ

Analysis Update

- Top-Up with 78% more antineutrino (RHC) data!
- See talk by Jeremy Wolcott at the 52nd Annual Fermilab Users Meeting
  - June 12-13, 2019 at Fermi National Accelerator Laboratory



Testbeam Detector

- Scaled-down version of NOvA detector at Fermilab Test Beam Facility
- Exposed to a new tertiary beam of pions, protons, muons, and electrons with known energies.
- Address energy-related and detector response systematics.
- Build a database of single particle topologies to tune reconstruction and train future convolutional neural networks for particle ID.
- Constructed and beginning data-taking operations soon!

- NOvA neutrino (8.85×10^{20} POT) and antineutrino data (6.9×10^{20} POT) analyzed.
  - Analysis with additional antineutrino data to be released ***next week!***
- We observe > 4σ evidence of electron antineutrino appearance.
- A joint appearance and disappearance analysis for these data:
  - Prefers Normal Hierarchy at 1.8 σ and excludes $\delta_{CP} = \pi/2$ at > 3σ.
  - Rejects maximal mixing at 1.8 σ and the lower octant at a similar level.

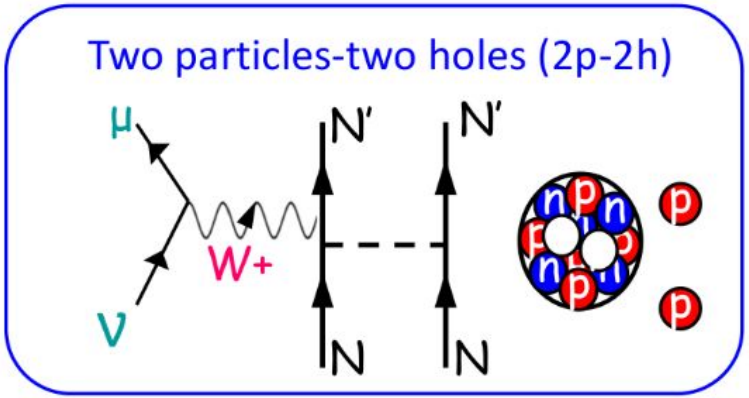
- Running planned through 2024, with proposed accelerator improvement projects and a test beam program to enhance ultimate reach.
  - Future NOvA running can reach 3σ sensitivity for the mass hierarchy by 2020 for some oscillation parameter values and covers significant δ_{CP} range by 2024.

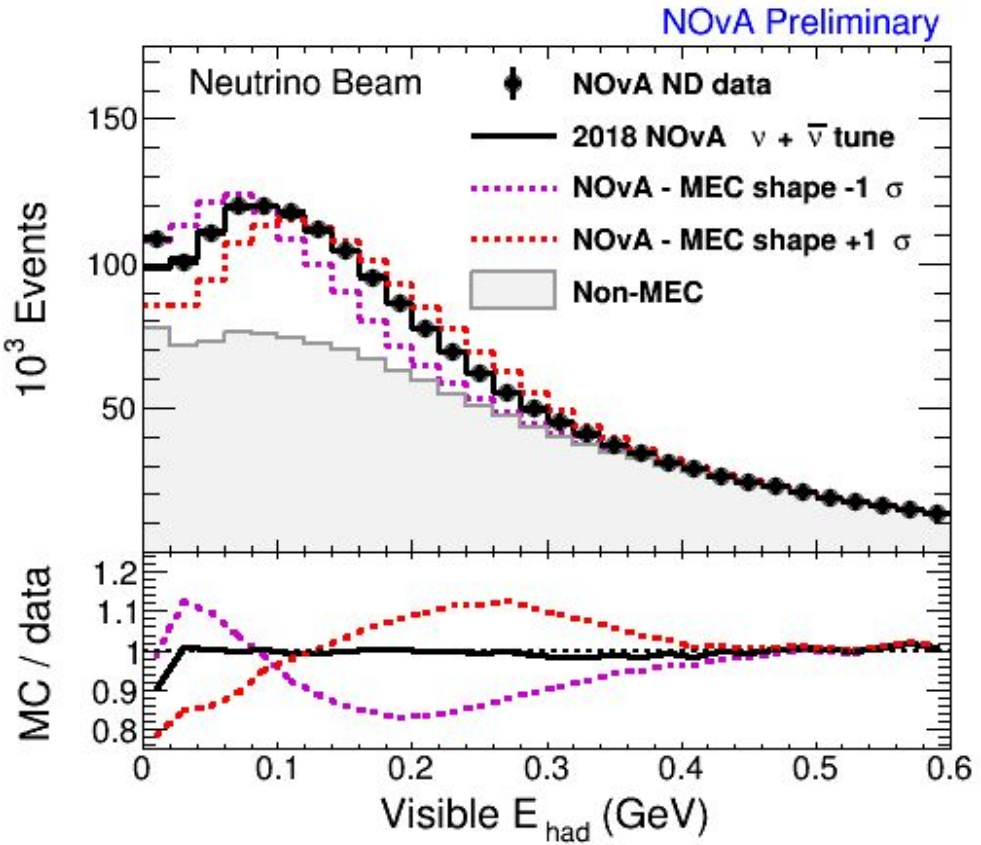
Backup

NOvA is sensitive to challenging intranuclear processes.

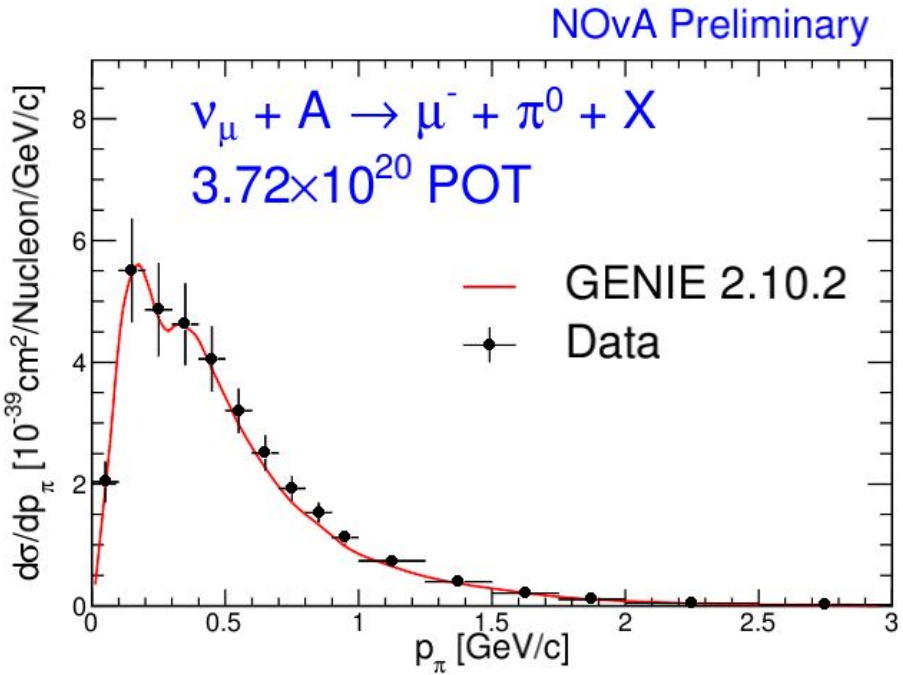
→ Under active investigation in the 1-2 GeV neutrino energy range

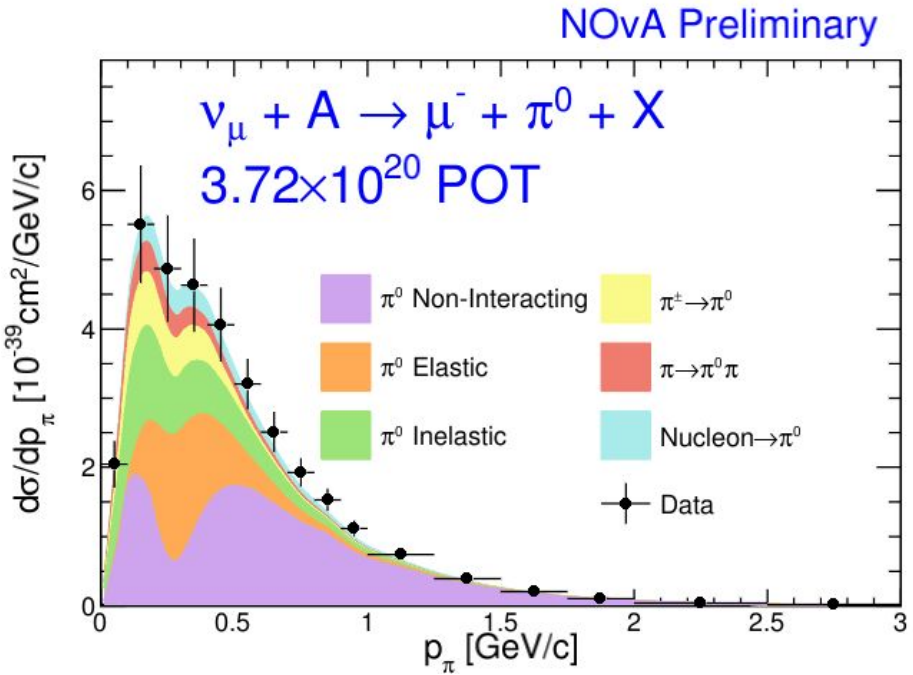
→ Data-driven tune of GENIE MEC model

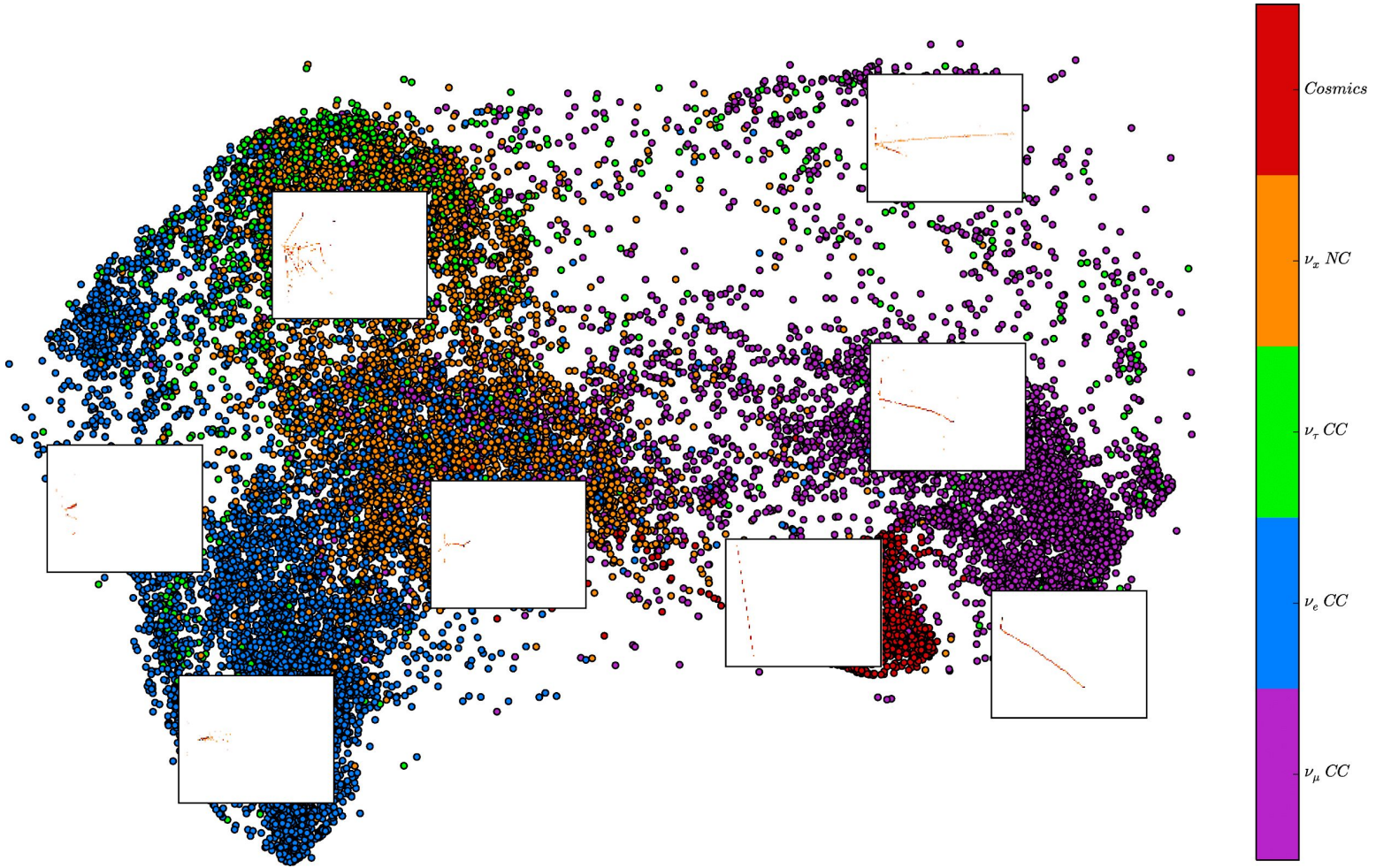




Measurements of neutrino interaction cross sections and nuclear effects are underway.

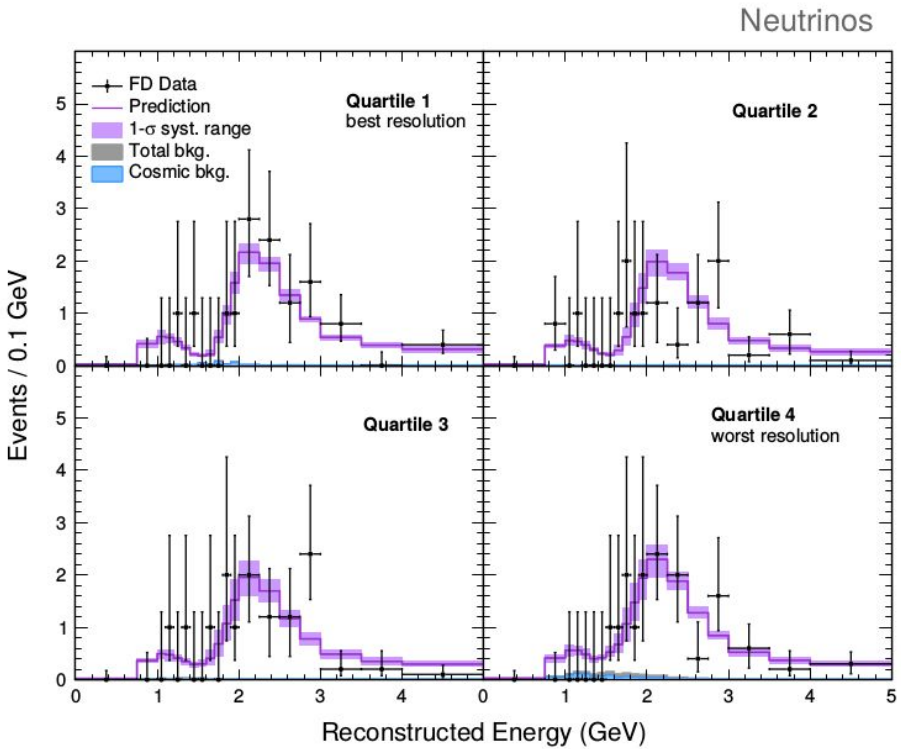


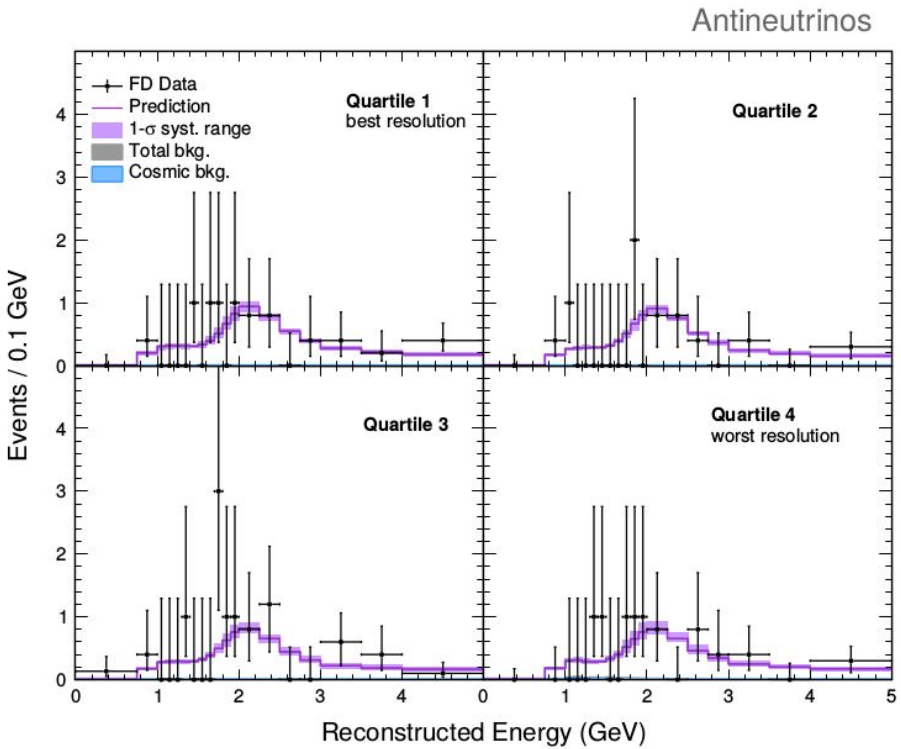



Cosmics
ν_x NC
ν_τ CC
ν_e CC
ν_μ CC

Predicted and measured neutrino spectra at the NOvA Far Detector

Extrapolated and fit in subsets by hadronic energy fraction





- Running 50% neutrino / 50% antineutrino going forward.
- Extended running through 2024, with proposed accelerator improvements and a testbeam program to enhance reach.

- Anticipate 3σ sensitivity to hierarchy (if NH and $\delta_{CP} = 3\pi/2$) for allowed range of θ_{23} by 2020.
- Anticipate 3σ sensitivity for 30-50% of δ_{CP} range (depending on octant) by 2024.

- Expect > 2σ sensitivity for CP violation in both hierarchies at $\delta_{CP} = 3\pi/2$ or $\delta_{CP} = \pi/2$ (assuming unknown hierarchy) by 2024.