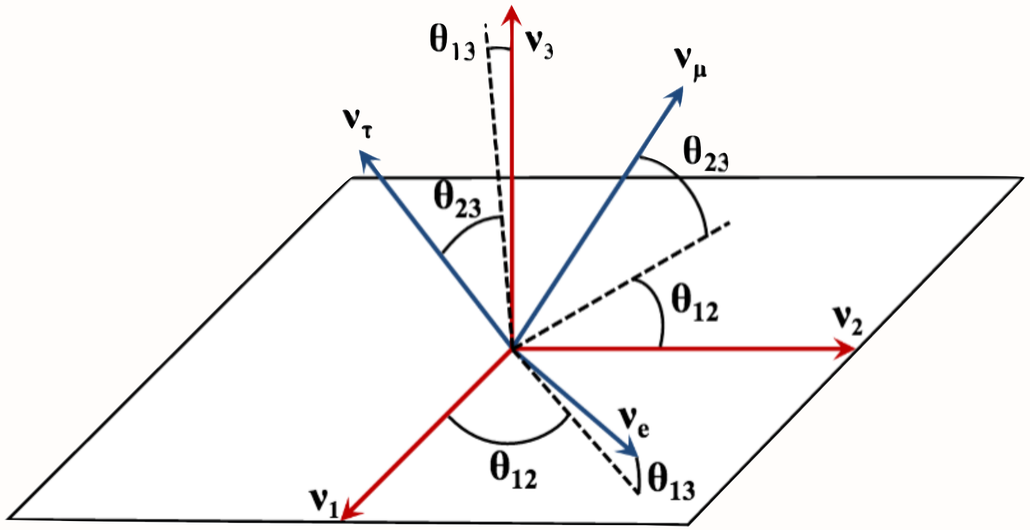
NOvA in ten minutes.

Justin Vasel
Indiana University

for the NOvA collaboration

Neutrinos

1930: Pauli proposes the neutrino
1956: First neutrino detection
1998: Discovery of neutrino oscillations



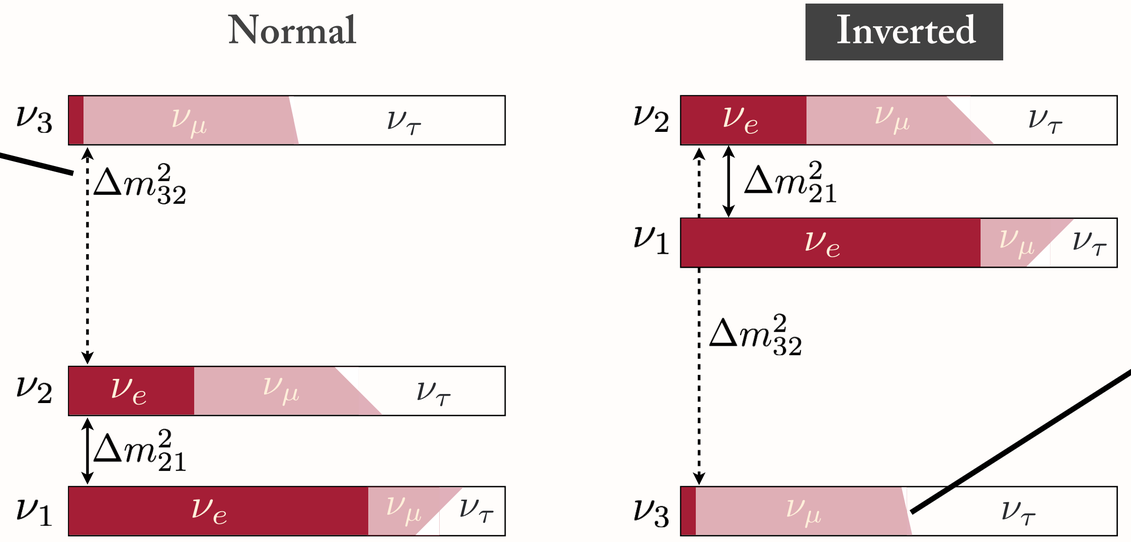
$$U = \begin{pmatrix} 1 & & \\ & cos\theta_{23} & sin\theta_{23} \\ & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & & sin\theta_{13}e^{-i\delta} \\ & 1 & \\ -sin\theta_{13}e^{i\delta} & & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & \\ -sin\theta_{12} & cos\theta_{12} & \\ & & 1 \end{pmatrix}$$

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

Primary physics goals of NOvA

CP violation
is there a difference between neutrinos and anti-neutrinos?

Mass hierarchy
normal or inverted?



θ_{23} octant determination
is μ/τ mixing maximal?

Additional Physics

- sterile neutrino searches
- cross-section measurements
- supernova neutrino detection
- monopole searches
- indirect dark matter searches
- short-baseline ν_τ appearance
- n–nbar oscillations
- cosmic-ray physics
- *and more!*

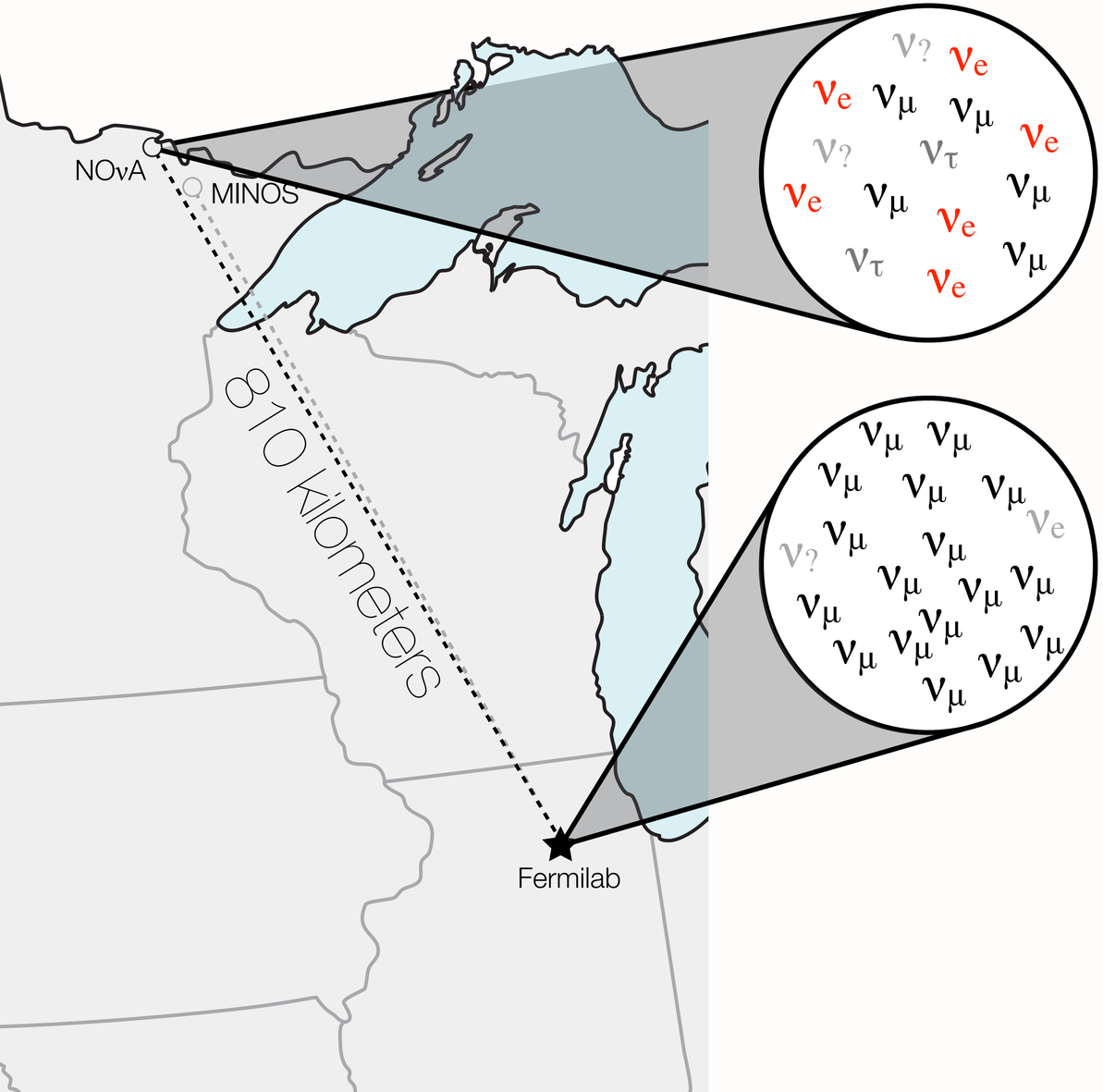
The NOvA Collaboration, 2018

240+ collaborators • **50** institutions • **7** countries

http://novaexperiment.fnal.gov

The NOvA Experiment

NuMI Off-axis ν_e Appearance



NOvA is an accelerator-based neutrino oscillation experiment.

two functionally-equivalent detectors
- segmented, sampling calorimeters
- liquid scintillator
- separated by ~810 km
- off-axis by 14 mrad

long-baseline

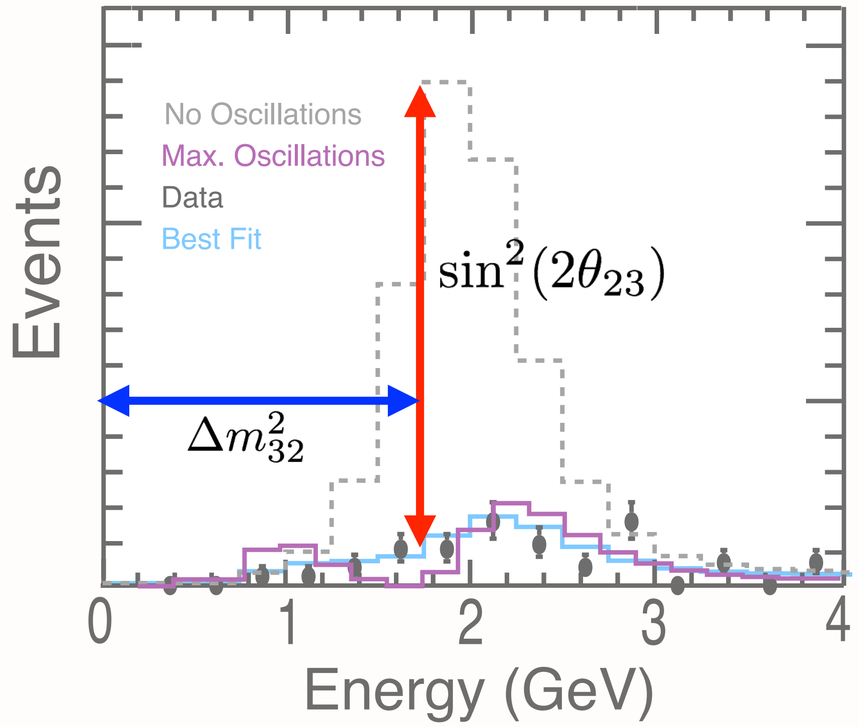
NOvA studies oscillations through $\nu_\mu \rightarrow \nu_\mu$ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance, and their antineutrino equivalents.

The game plan

From theory, one can approximate the $\overset{(-)}{\nu}_\mu$ **disappearance** probability as

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267\ \Delta m^2_{32}\ \frac{L}{E}\right)$$

This channel gives us sensitivity to the $\theta_{23} - \Delta m^2_{32}$ parameter space.



The $\overset{(-)}{\nu}_e$ **appearance** probability:

$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{\text{atm}}} e^{-e(\Delta_{32} + \delta_{CP})} + \sqrt{P_{\text{sol}}} \right|^2$$

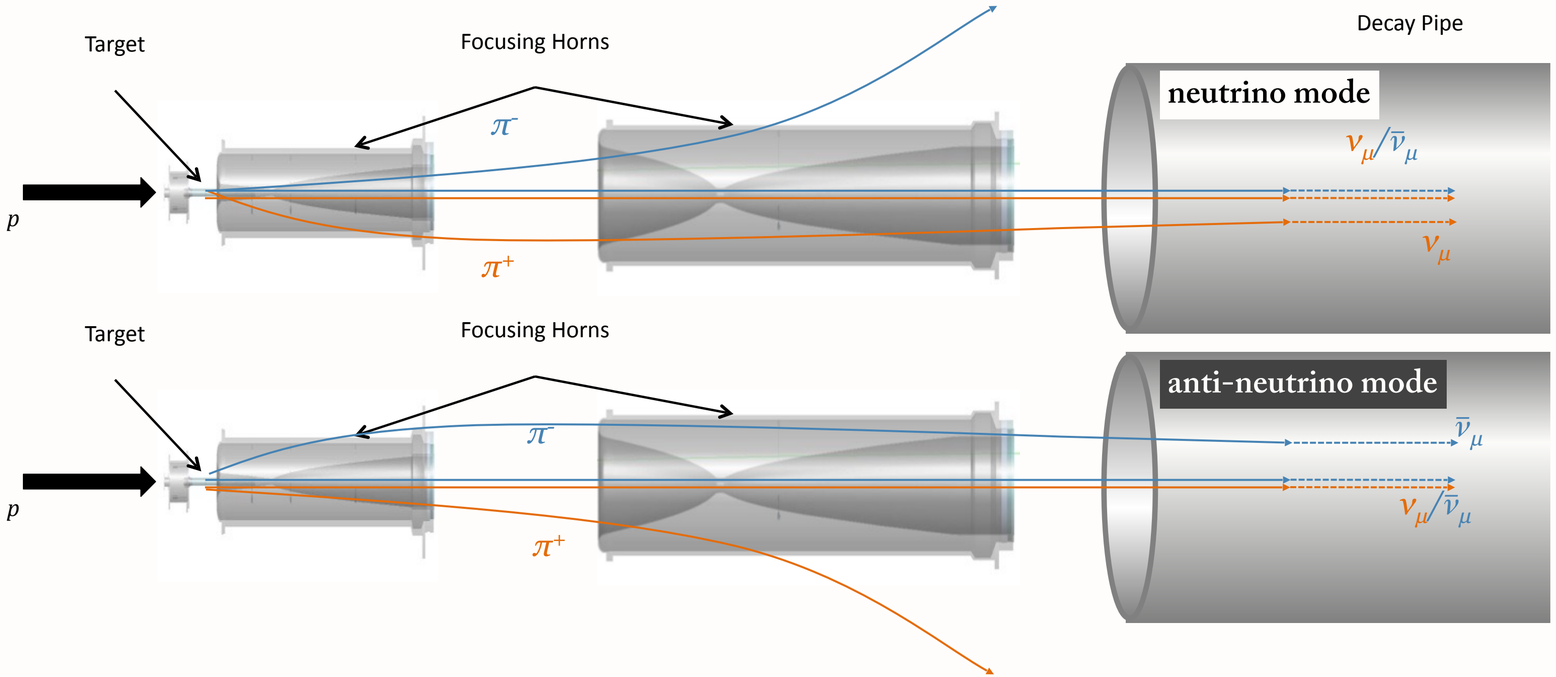
$$\approx P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} \left(\cos\Delta_{32} \cos\delta_{CP} \mp \sin\Delta_{32} \sin\delta_{CP}\right)$$

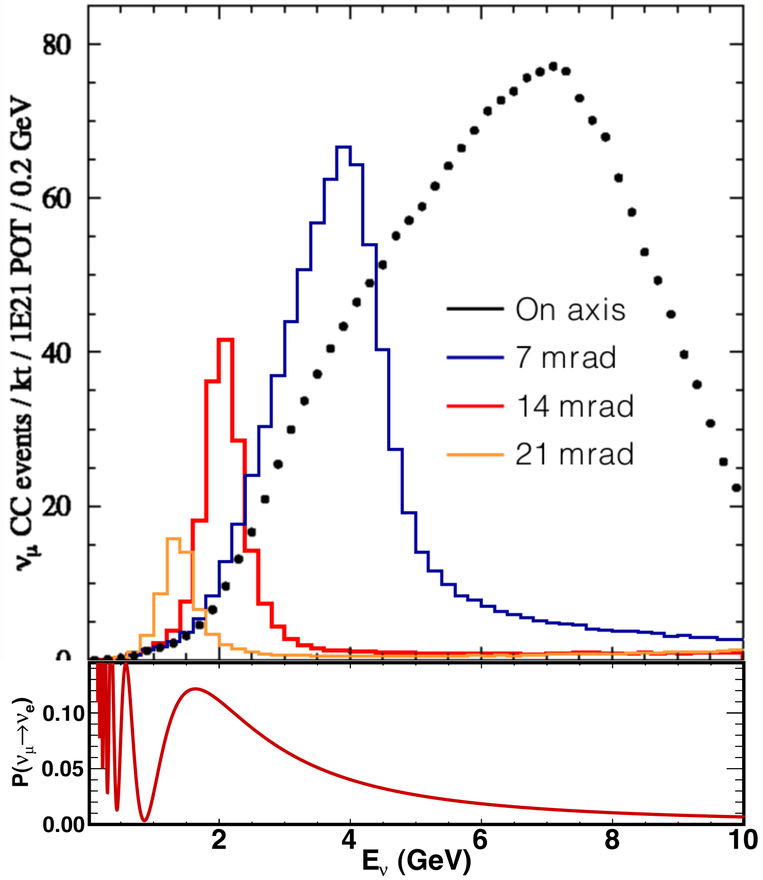
access to δ_{CP}

Many other oscillation/mixing parameters contained in these other terms.

NuMI neutrino beam

Neutrinos at the Main Injector (Fermilab)





- produced by colliding 120 GeV protons with a graphite target.
- magnetic focusing horns select for charge of the produced pions/ kaons and collimate the beam.
- mesons soon decay into neutrinos.
- the most powerful neutrino beam in the world.
- **horn polarity can be used to produce neutrinos or antineutrinos.**

The off-axis advantage:

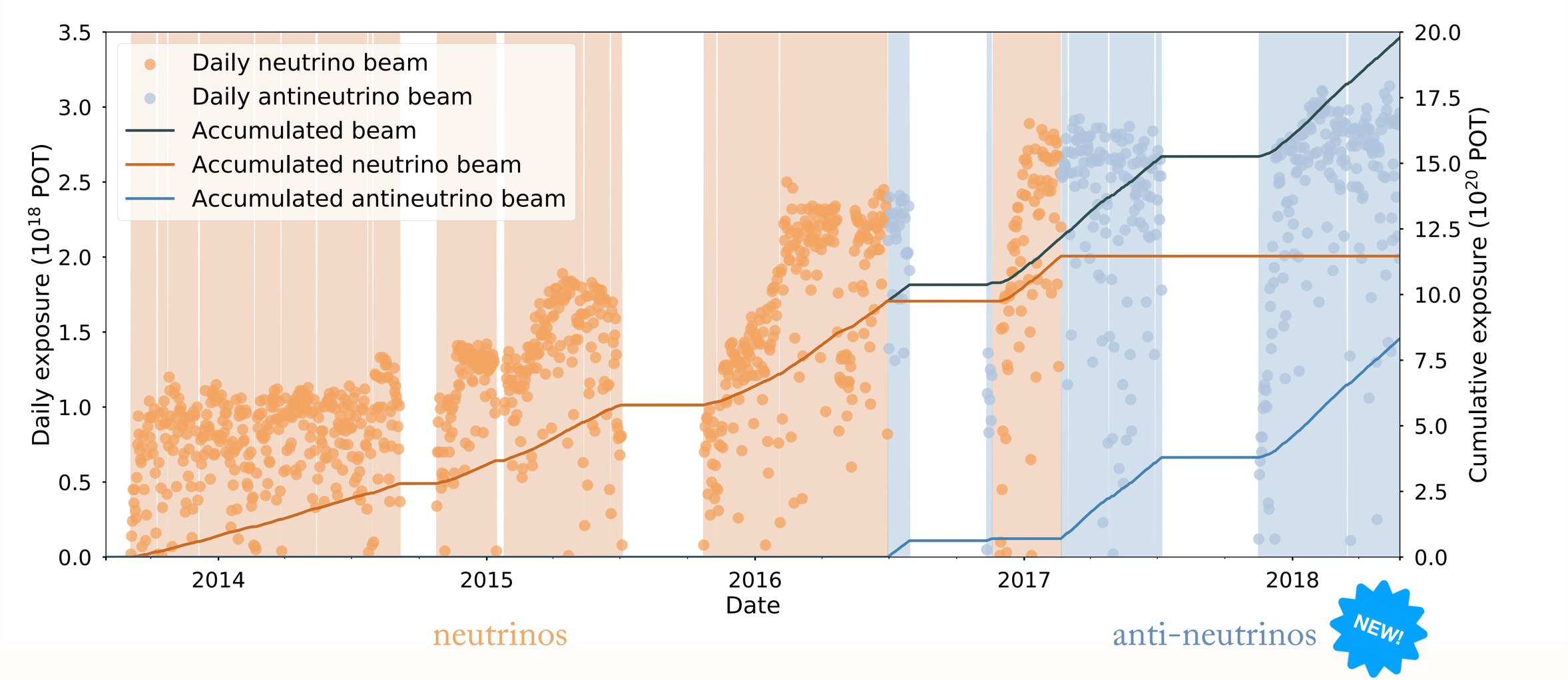
- Neutrino beam is narrowly peaked near oscillation maximum.
- Reduced neutral-current backgrounds
- Reduced wrong-sign beam contamination

Beam exposure

beam power now routinely greater than 700 kW.

first anti-neutrinos in mid-2016.

beam exposure in latest analysis:
ν: 8.85 x 10^{20} POT (protons-on-target)
$\bar{\nu}$: 6.9 x 10^{20} POT



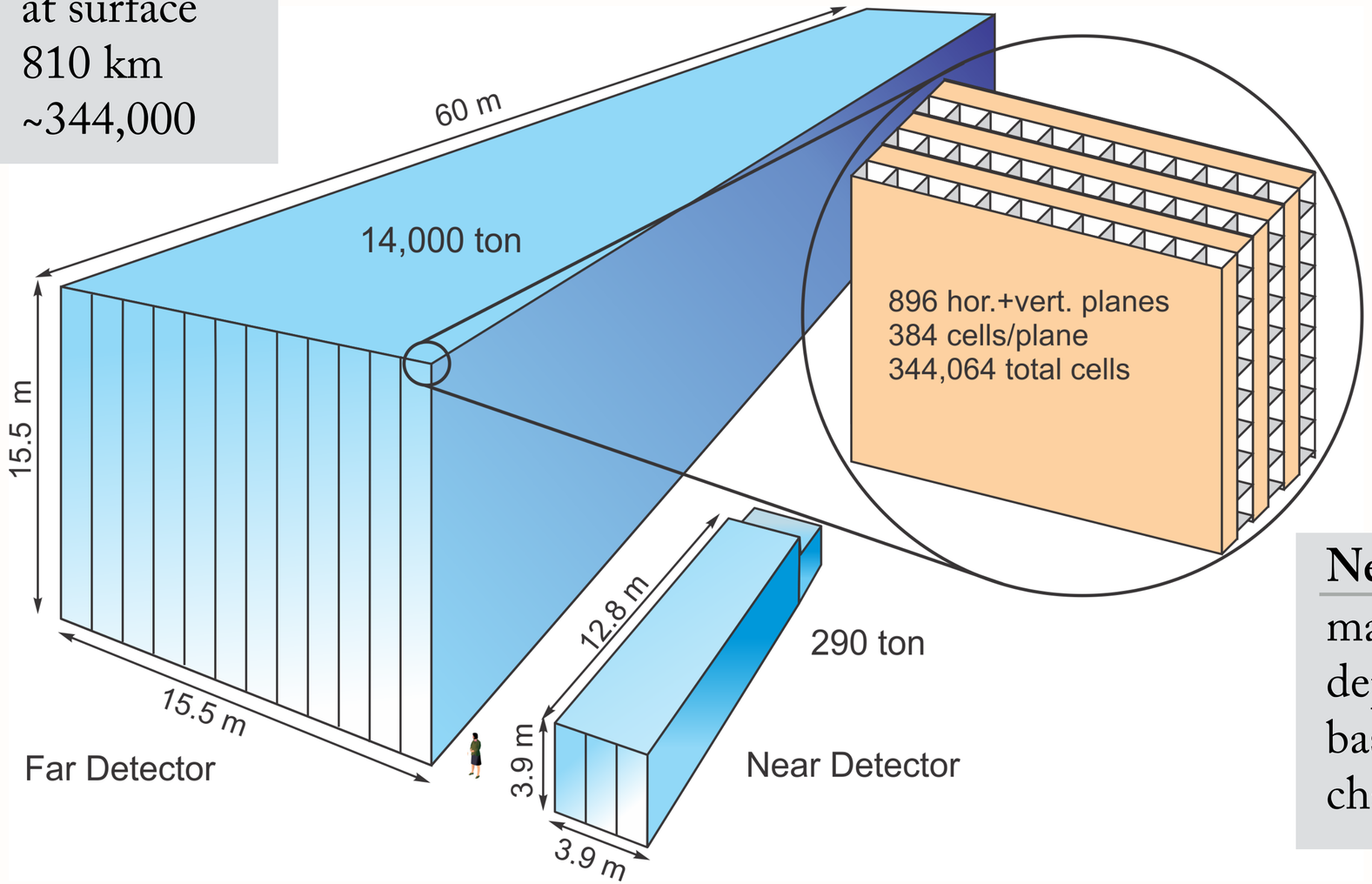
The NOvA detectors

Construction

- PVC plastic cells arranged into planes
- filled with liquid scintillator
- horizontal & vertical plane orientations provide a 3D view.
- 65% active mass

Far Detector (FD)

mass	14 kton
depth	at surface
baseline	810 km
channels	~344,000



Near Detector (ND)

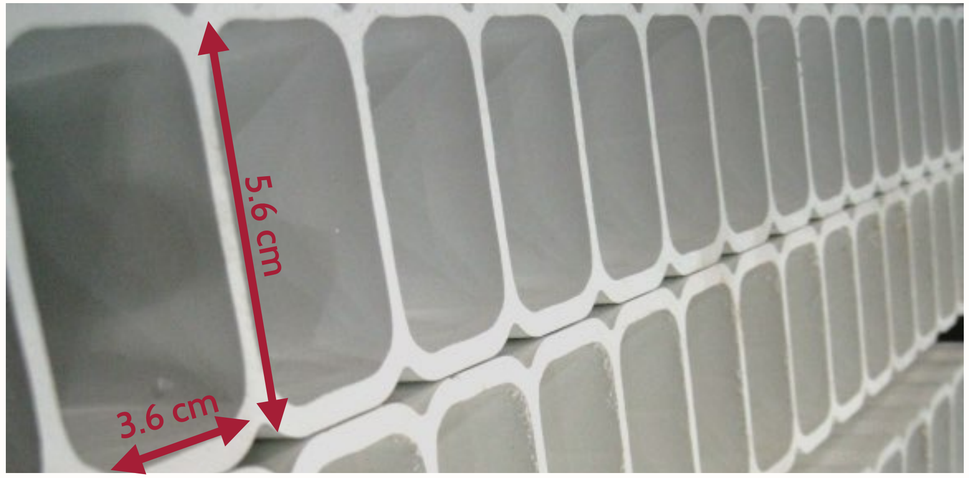
mass	290 ton
depth	100 m
baseline	1 km
channels	~20,000

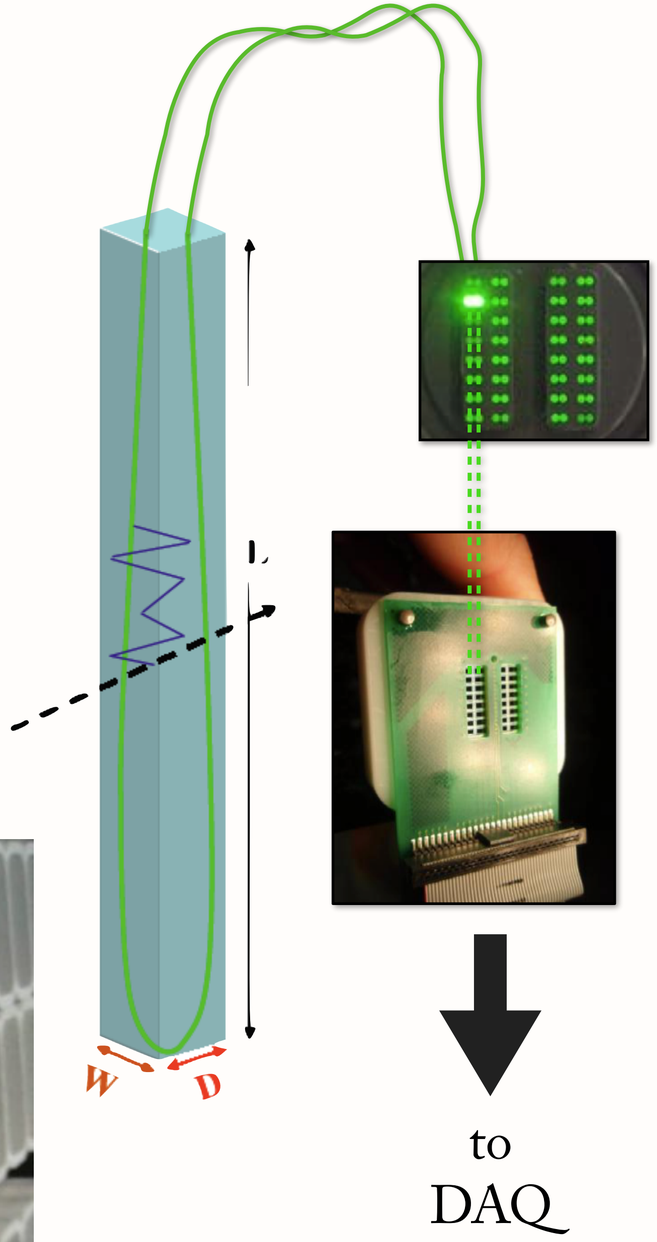
The NOvA detectors

Active interaction medium is **liquid scintillator** with pseudocumene and PPO.

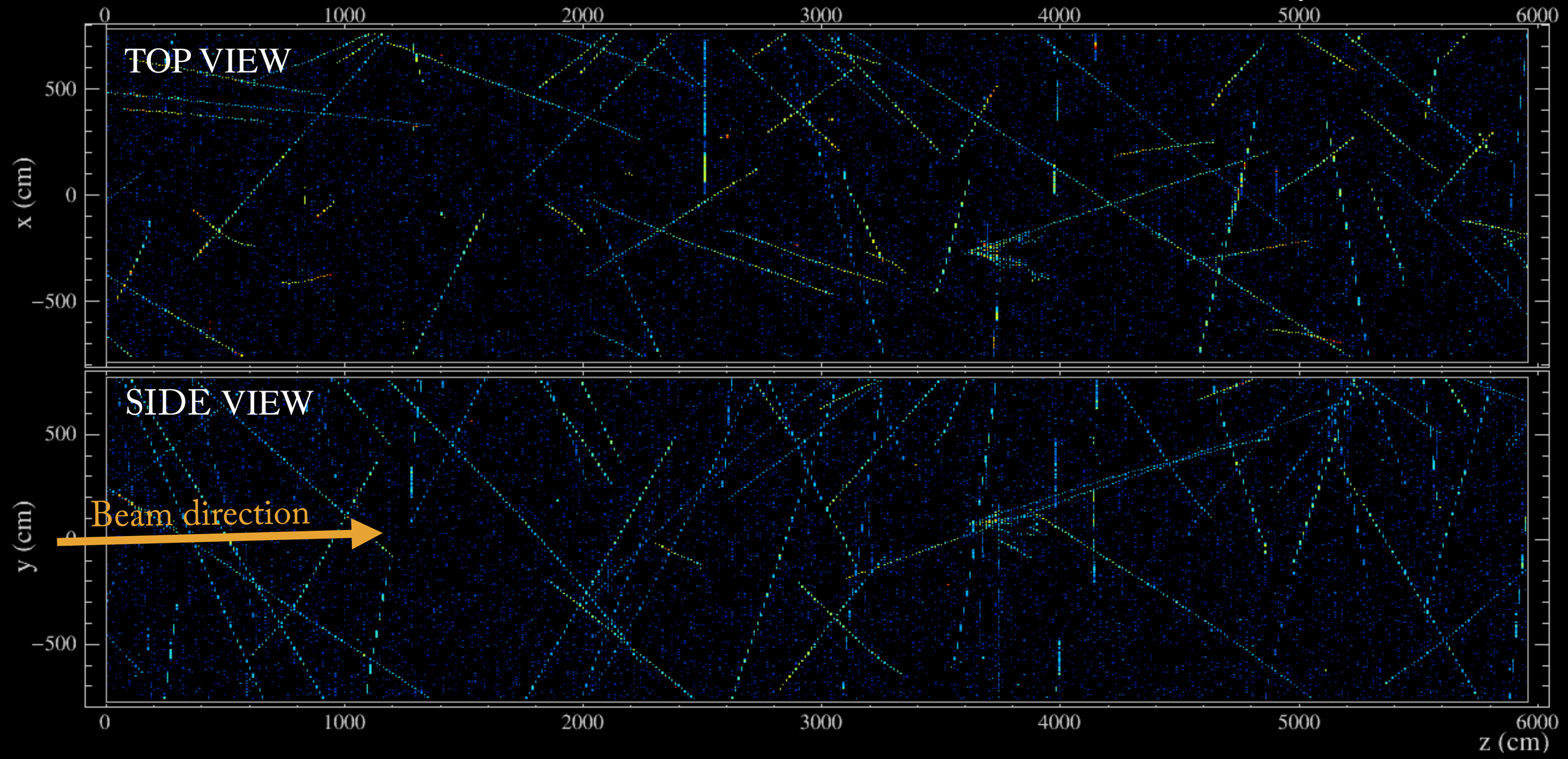
Each cell has a single **wavelength-shifting fiber** looped inside it.

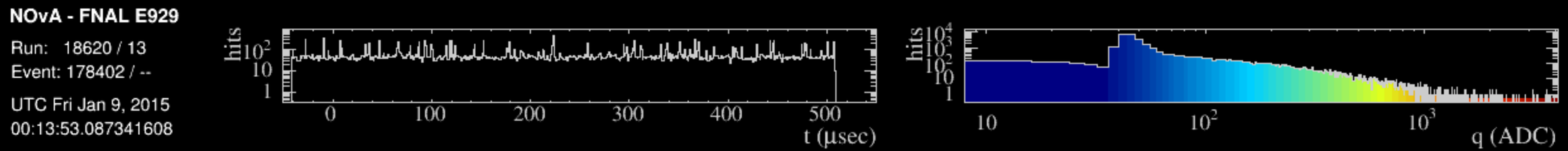
The two free ends of the fiber attach to an **avalanche photodiode,** which is attached to a front-end board for signal detection/readout.

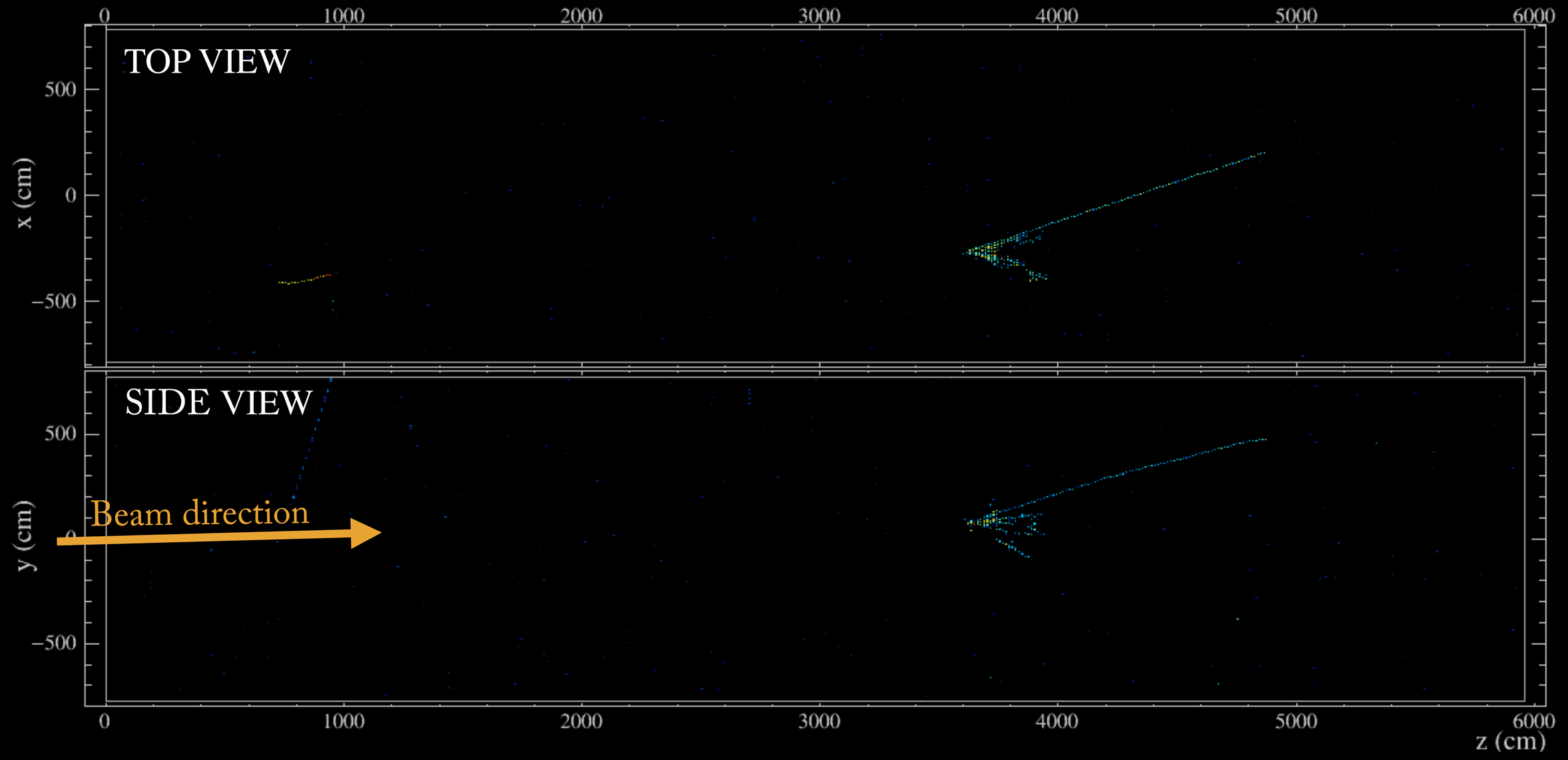




cosmic ray rate ~150 kHz



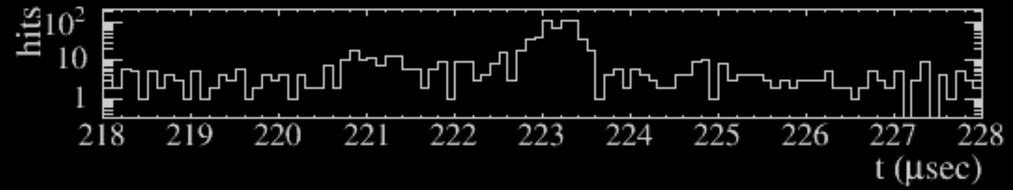


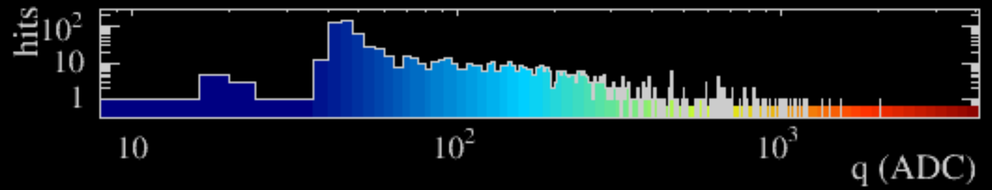


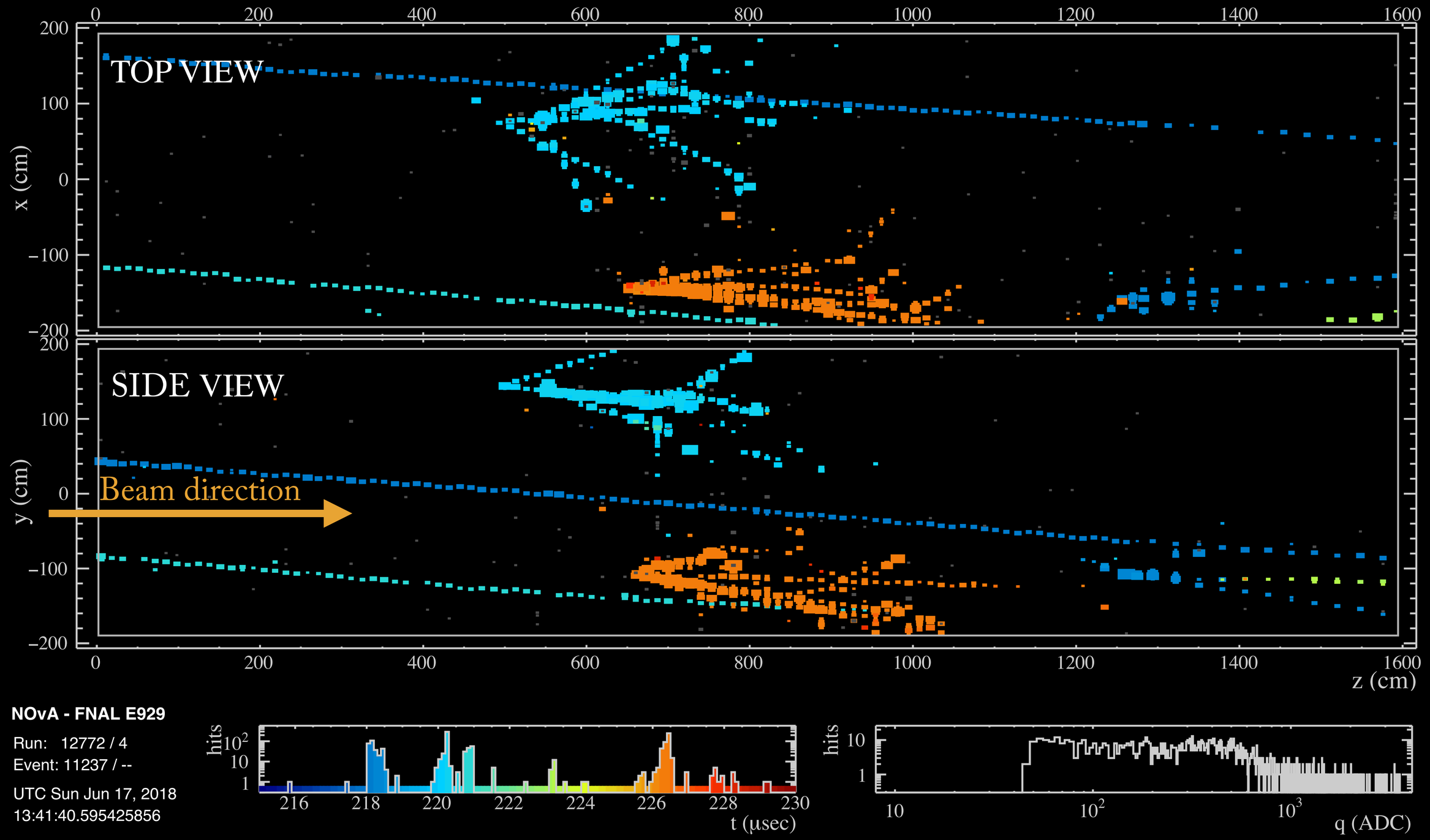
NOvA - FNAL E929

Run: 18620 / 13
Event: 178402 / --

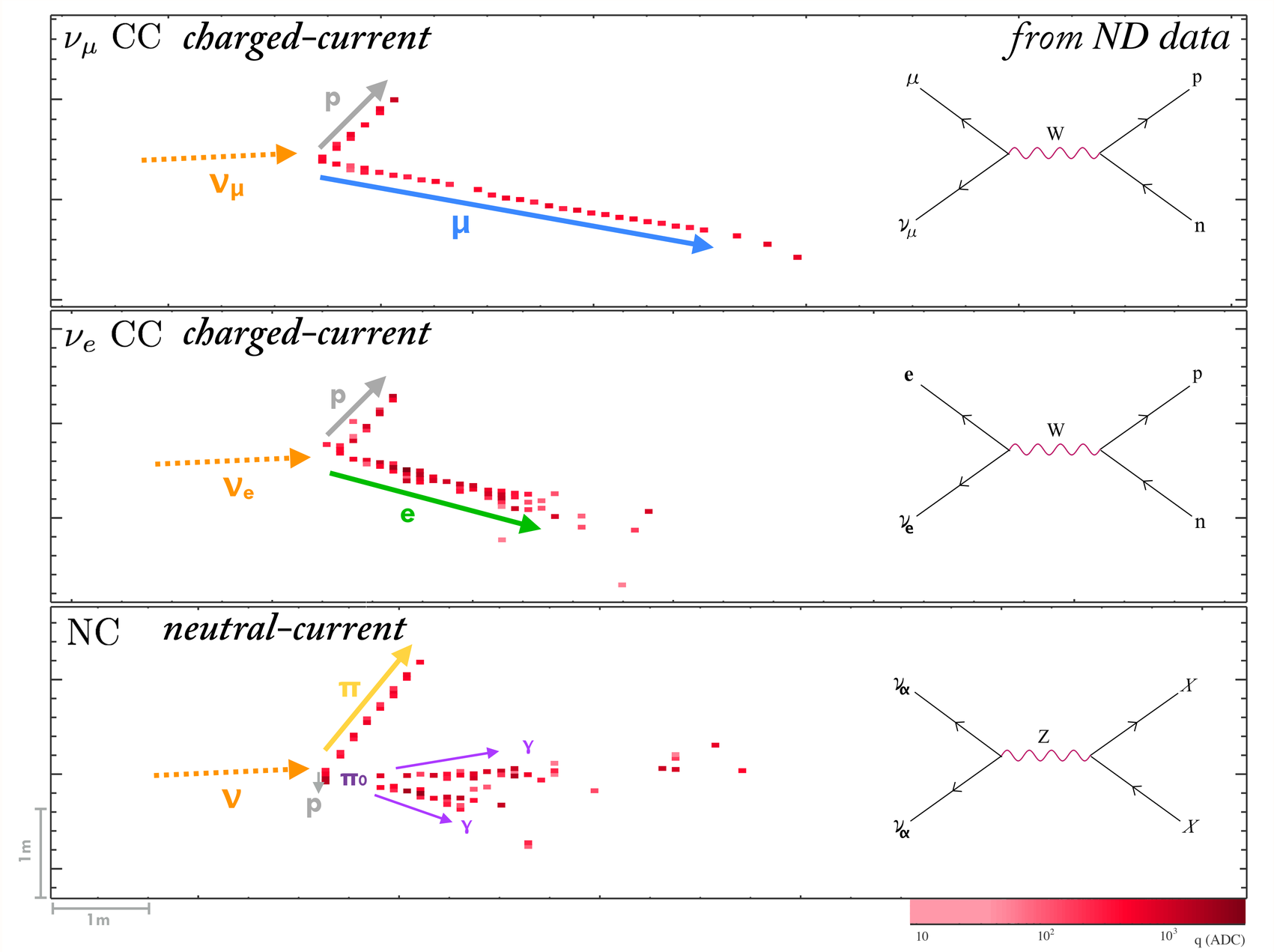
UTC Fri Jan 9, 2015
00:13:53.087341608






TOP VIEW
SIDE VIEW
Beam direction
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 12772 / 4
Event: 11237 / --
UTC Sun Jun 17, 2018
13:41:40.595425856
hits
t (μsec)
q (ADC)

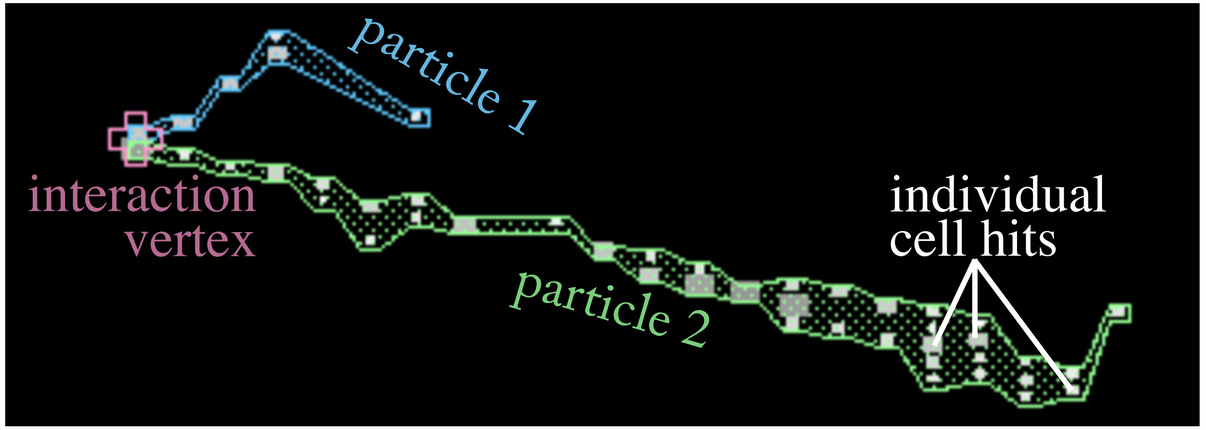
Event topologies



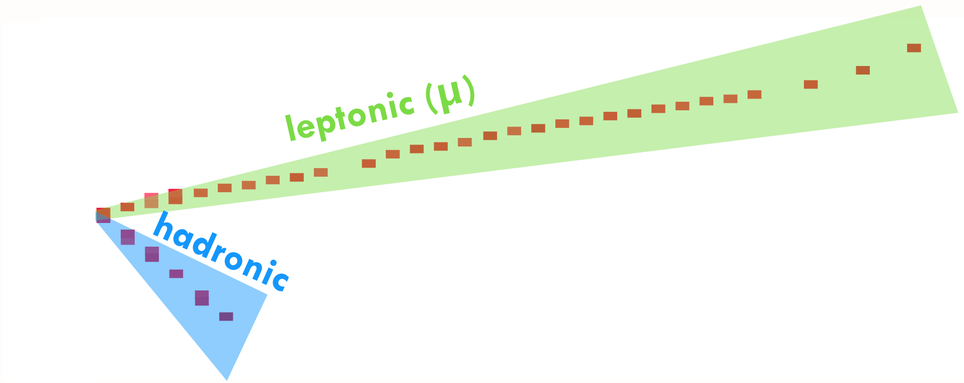
Event selection & reconstruction

In a nutshell…

- group hits close in space/time
- find track-like structures
- identify the vertex
- cluster the hits from individual particle tracks
- use deep-learning algorithms to tag event type
- reconstruct energy of each particle



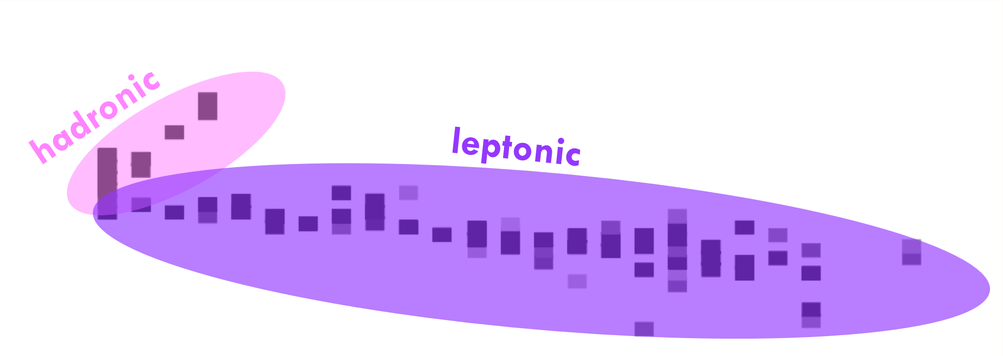
ν_μ energy reconstruction



sum **leptonic** & **hadronic** energies

μ energy based on track-length

ν_e energy reconstruction



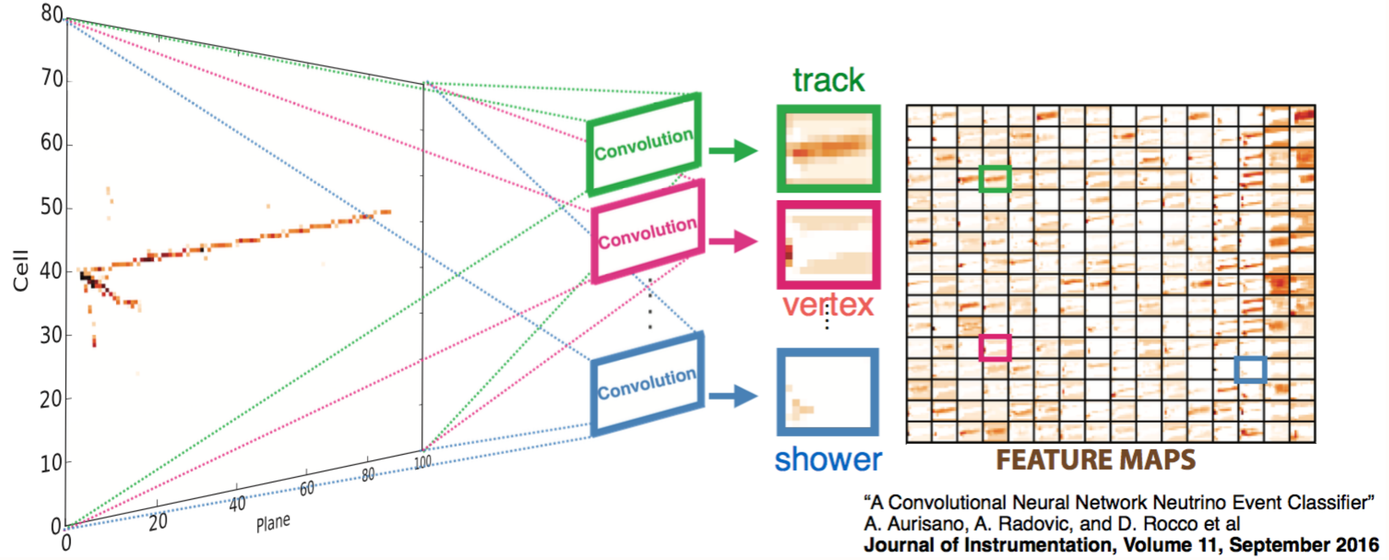
sum **leptonic** & **hadronic** energies

both energies are calorimetrically reconstructed.

Deep learning at NOvA

See talk by Micah Groh.

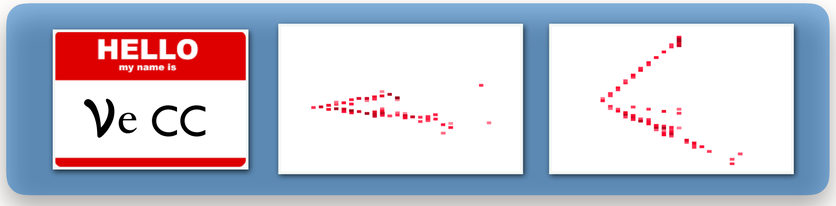
Convolutional Visual Network (CVN)
Was the first instance of using deep learning in a high-energy physics result.



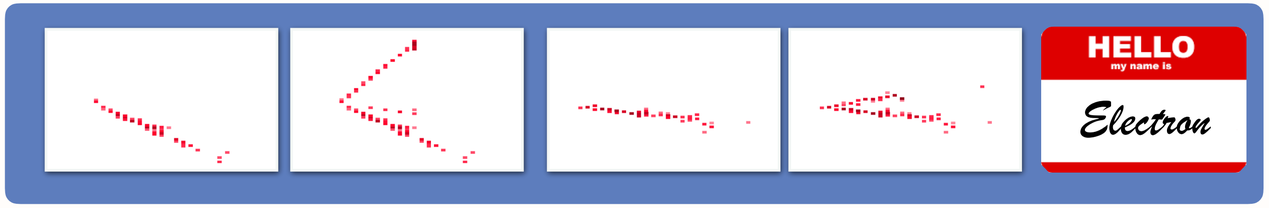
Paper: *"A convolutional neural network neutrino event classifier"* 2016 JINST 11 P09001

For more on our single-particle classifier, see:
FERMILAB-THESIS-2018-07

Convolutions are applied to **pixel maps** of our events, which are trained to identify particular features (tracks, vertex, showers, etc.). Output of this process is a score by category.



Event Classification
Determine which type of event a given interaction is

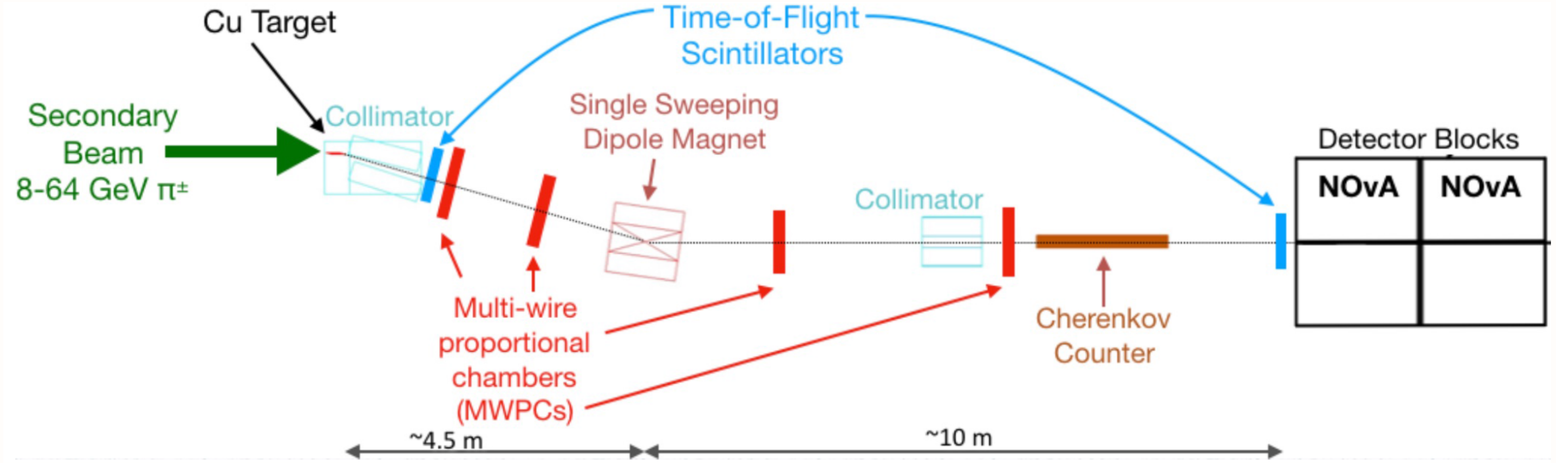


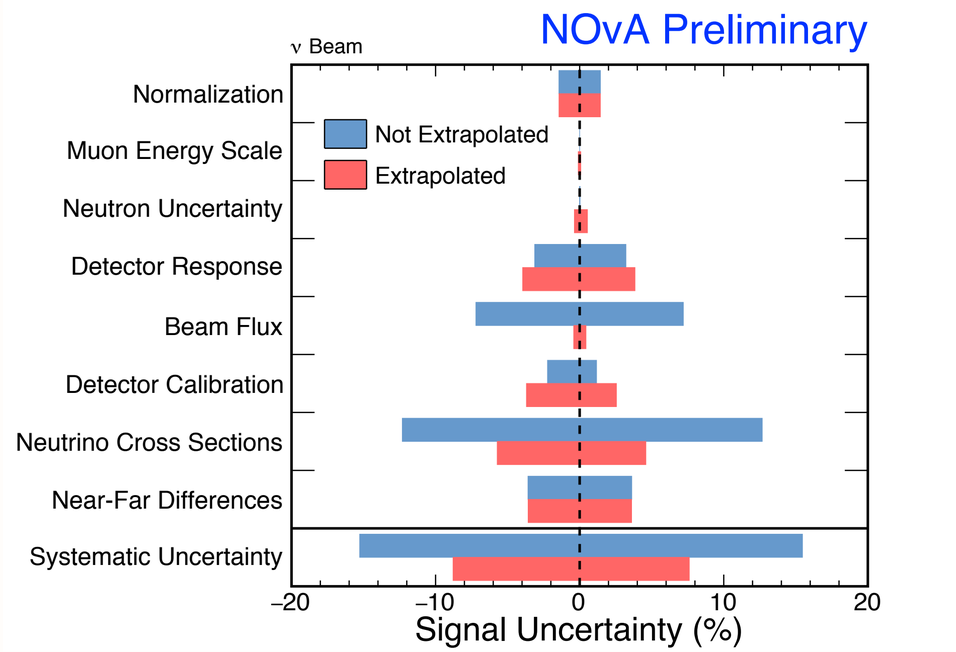
Particle Identification
Identify individual particles within an interaction event, using the full event topology for context.

Looking ahead

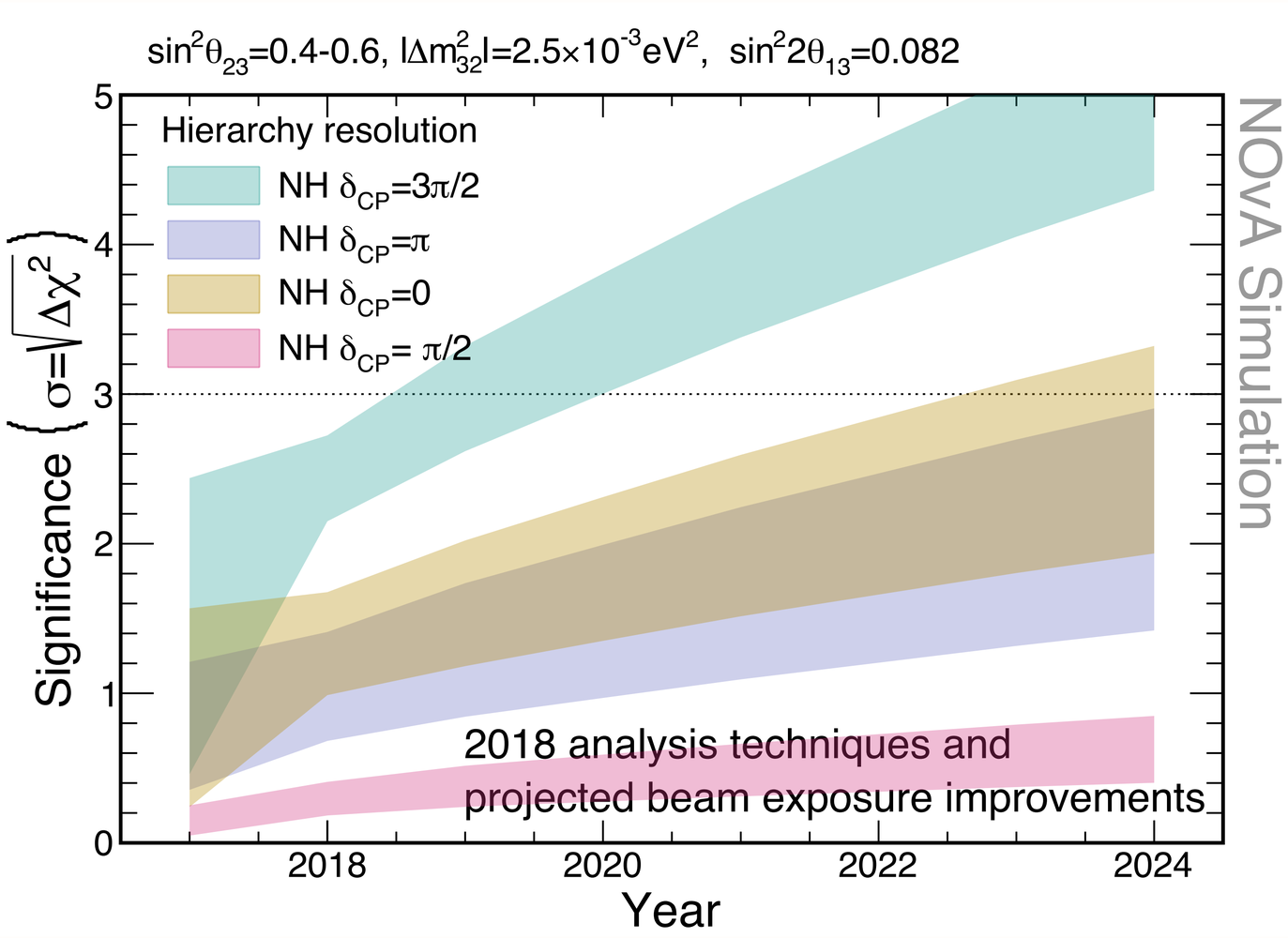
New test beam program will help us reduce detector-related **systematic uncertainties.**

Commissioning now; data-taking in 2019.





Looking ahead



projected sensitivities for remainder of experiment.

3σ sensitivity to hierarchy by 2020 if other parameters are favorable

2σ δ_{CP} sensitivity by 2024
(not shown on this plot)

Based on expected improvements to the analysis and beam exposure

Test beam program will help us reduce systematic uncertainties to achieve these sensitivities.

Further reading…

FERMILAB-PUB-18-223-ND

New constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in the NOvA experiment

NEW! Paper on our previous results. arxiv:**1806.00096**

New Perspectives

Micah Groh
NOvA Reconstruction using Deep Learning

Dmitrii Torbunov
NOvA Muon Disappearance Results 2018

Bruce Howard
New electron (anti-)neutrino appearance analysis from NOvA

Derek Doyle
Accelerating Feldman-Cousins on NOvA using NERSC Supercomputers

Jeremy Hewes
Search for sterile neutrinos in NOvA neutrino data

Rijeesh Keloth
NOvA's Short-Baseline Tau-Neutrino Appearance Search

51st Users Meeting

Evan Niner
NOvA plenary talk

Posters:

Reddy Gandrajula
First measurement of oscillation parameters with neutrino and antineutrino beam in NOvA

Dmitrii Torbunov
NOvA Muon Disappearance Results 2018

Sijith Edayath
Long Baseline Sterile Neutrino Search in the NOvA Experiment

Matt Judah
Status of the Incluse Electron and Muon Neutrino Charged-Current Cross-Section Measurements in the NOvA Near Detector

back-ups

Recent results with anti-neutrino data

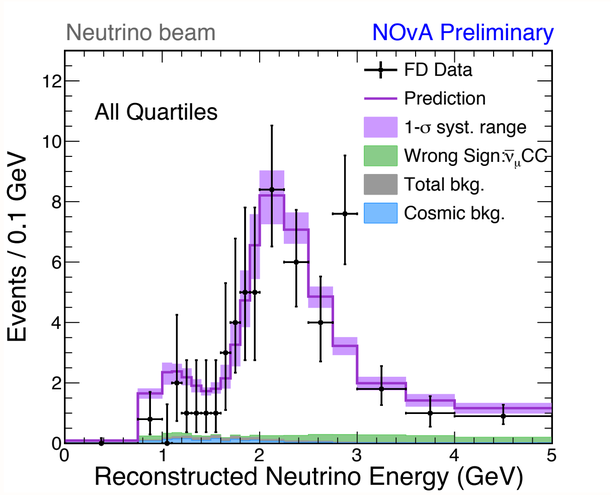
See talks by D. Torbunov, B. Howard, J. Hewes *neutrino + antineutrino*

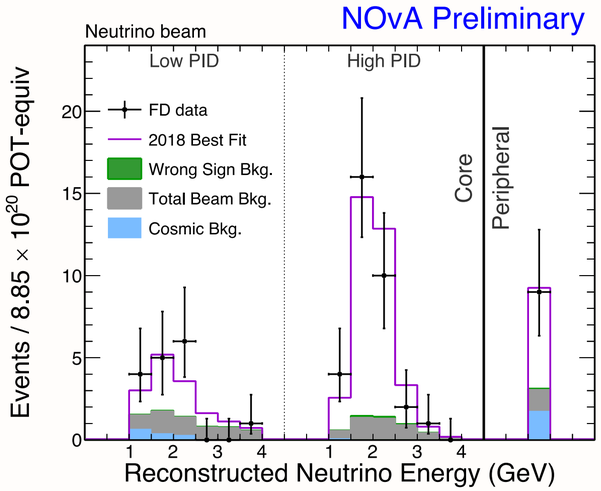
ν_μ disappearance

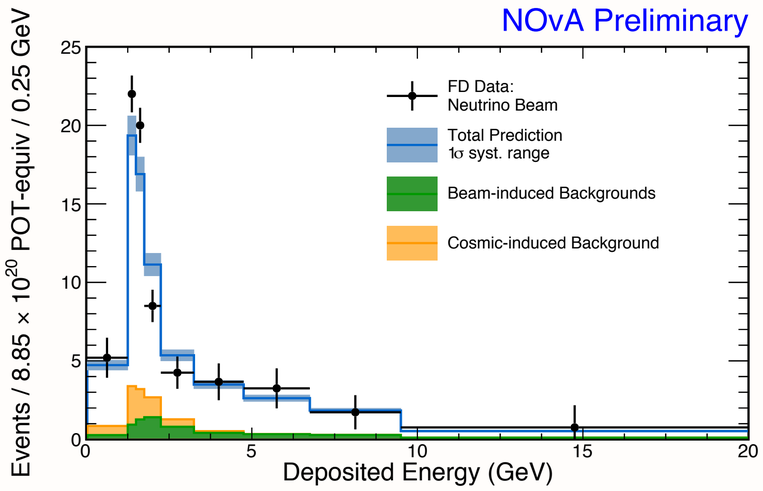
ν_e appearance

NC disappearance

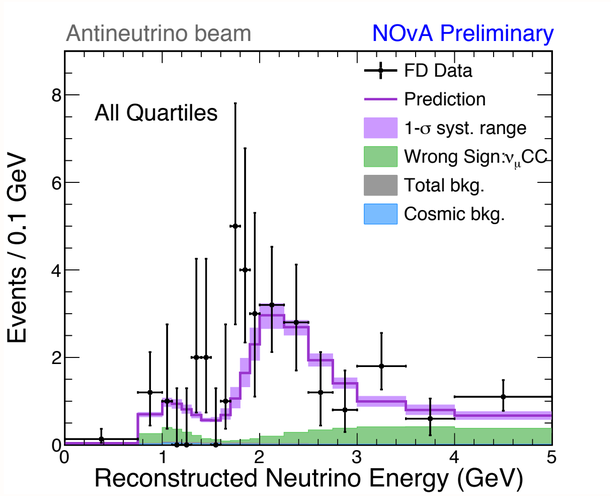
neutrinos

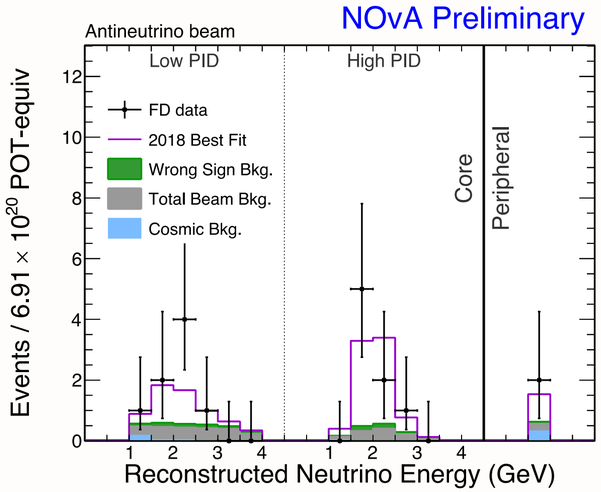


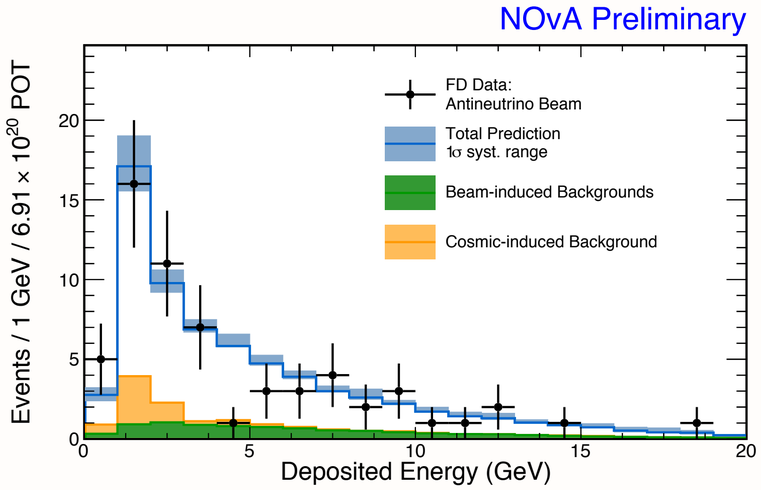




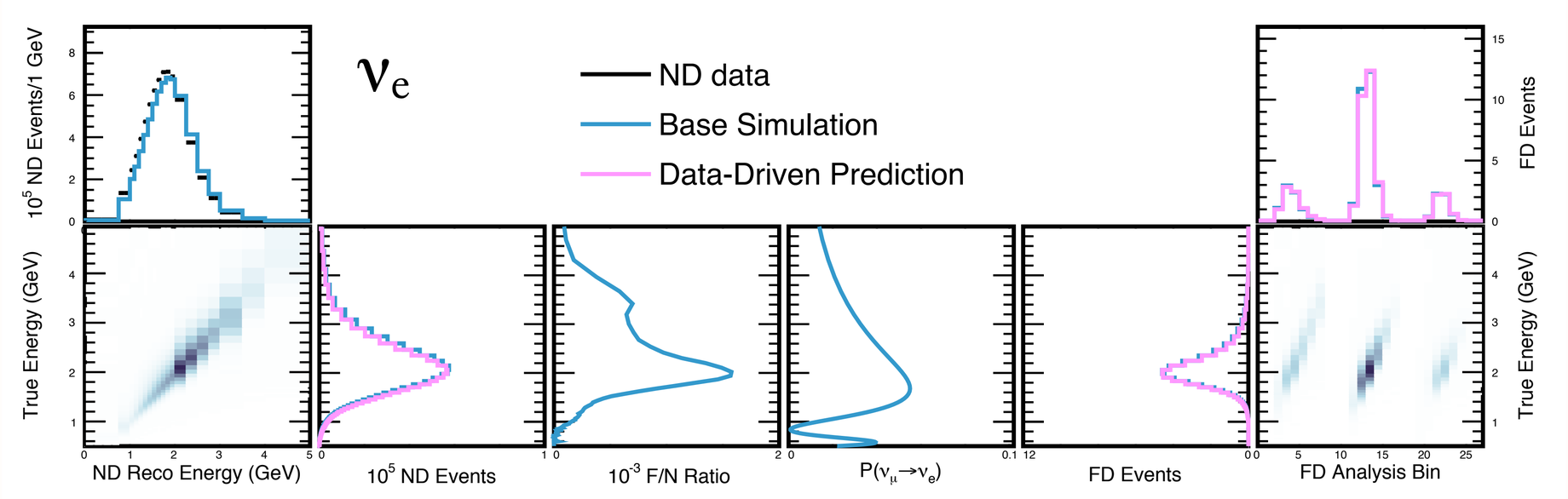
anti-neutrinos

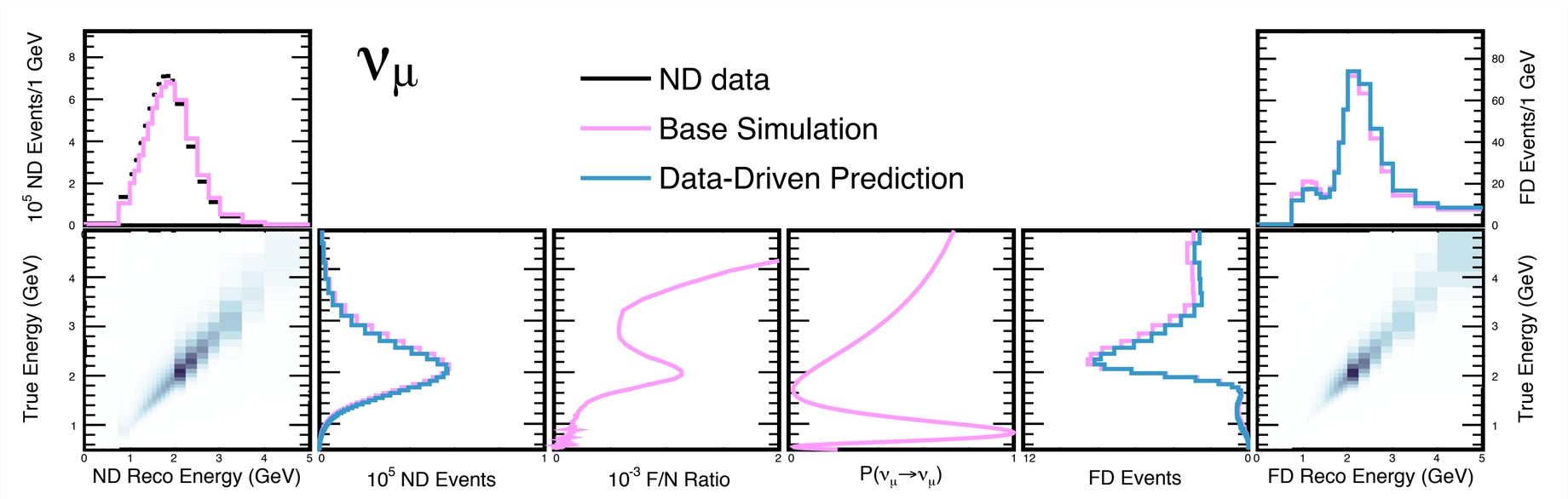
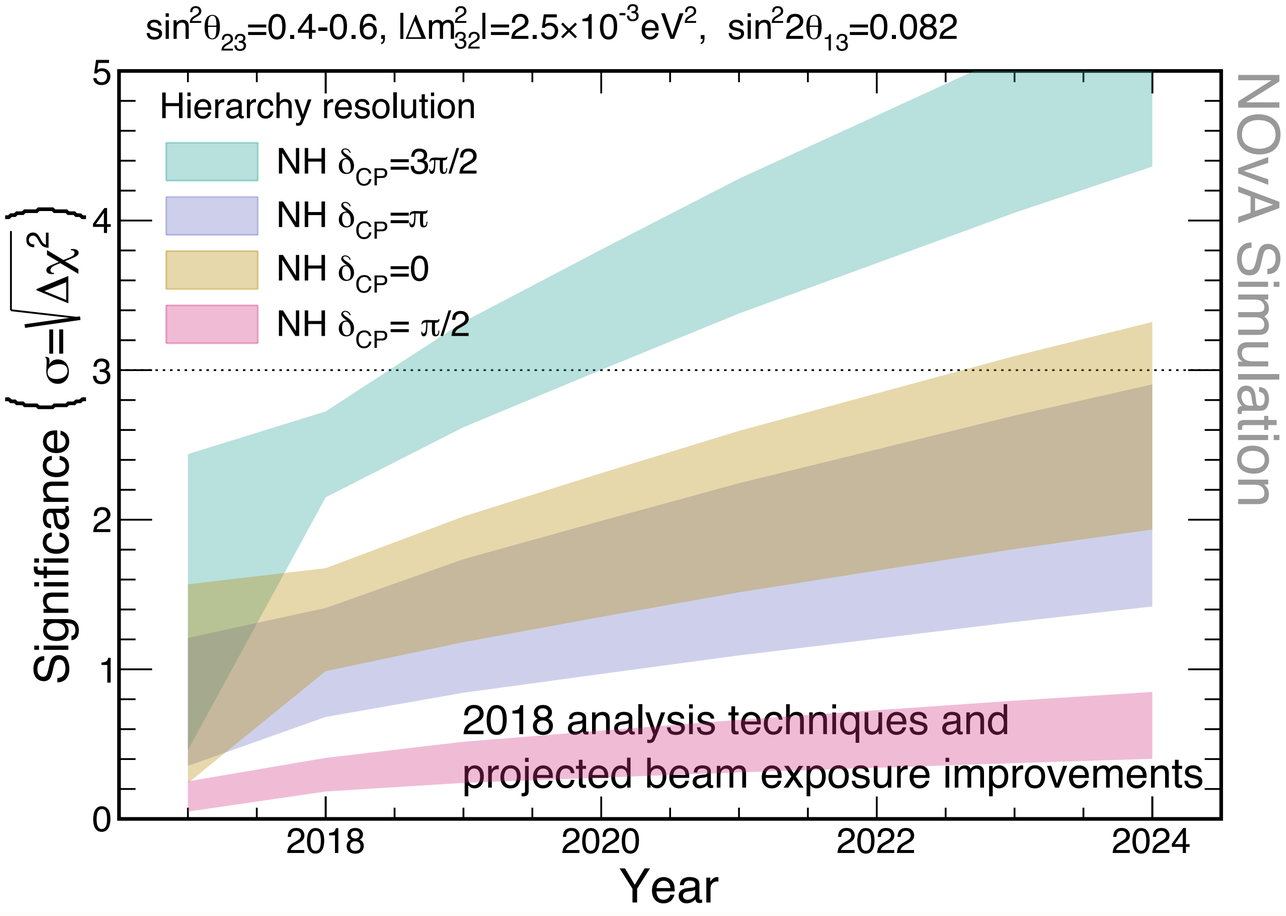
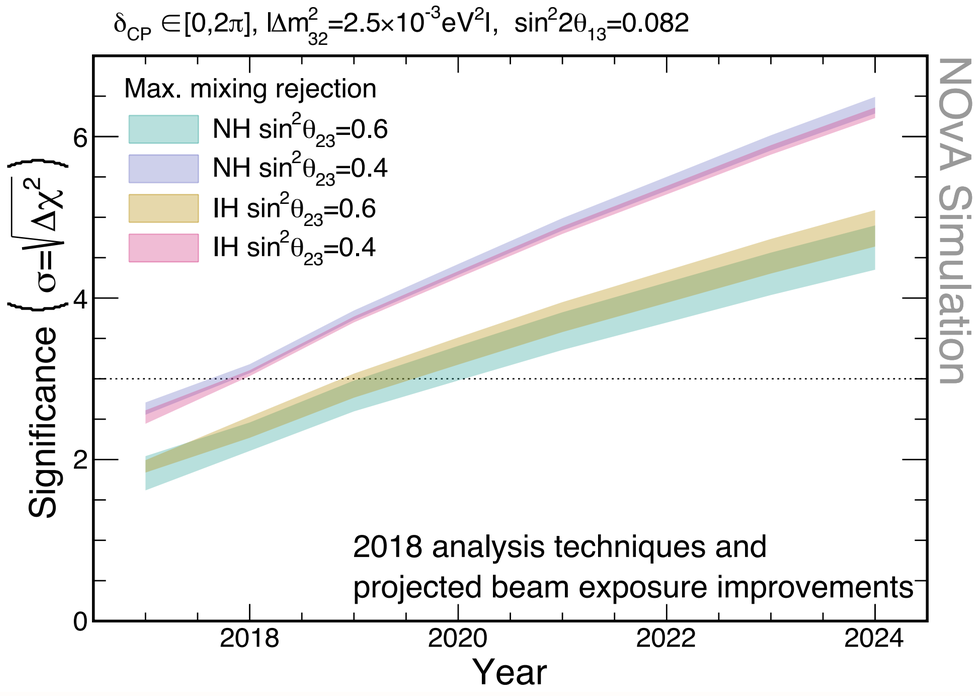
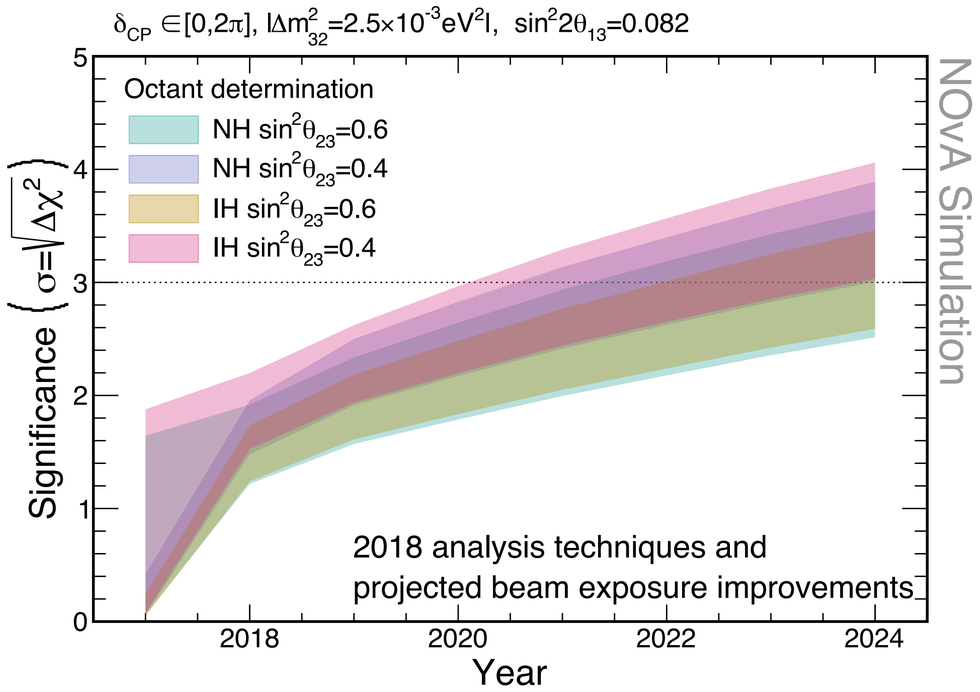






Near-far extrapolation





Future sensitivities