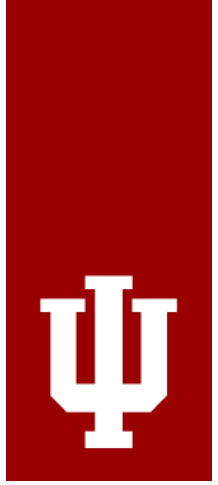


Neutrino Oscillation Results from the NOvA Experiment

Erica Smith for the NOvA Collaboration

Indiana University

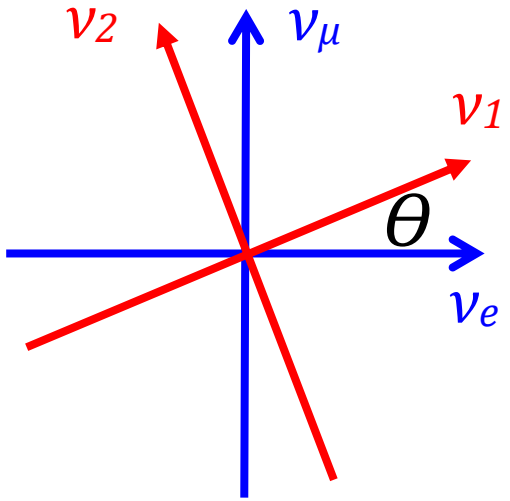
September 5, 2021

Neutrino Oscillations

Neutrinos are created in one flavor but can be detected in another:

Each flavor is a superposition of mass states:

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



Three-Flavor Oscillations

The mixing matrix (PMNS matrix) can be written in terms of 3 angles and 1 phase.
Usually factorized into components directly related to the experiments:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

- The (12) sector: Solar and Reactor, L/E 15,000 km/GeV
- The (23) sector: Atmospheric and Accelerator, L/E 500 km/GeV
- The (13) sector: Reactor and Accelerator, L/E 500 km/GeV

$\sin^2\theta_{23} = 0.545 \pm 0.021$

$\sin^2\theta_{13} = 0.0218 \pm 0.0007$

$\sin^2\theta_{12} = 0.307 \pm 0.013$

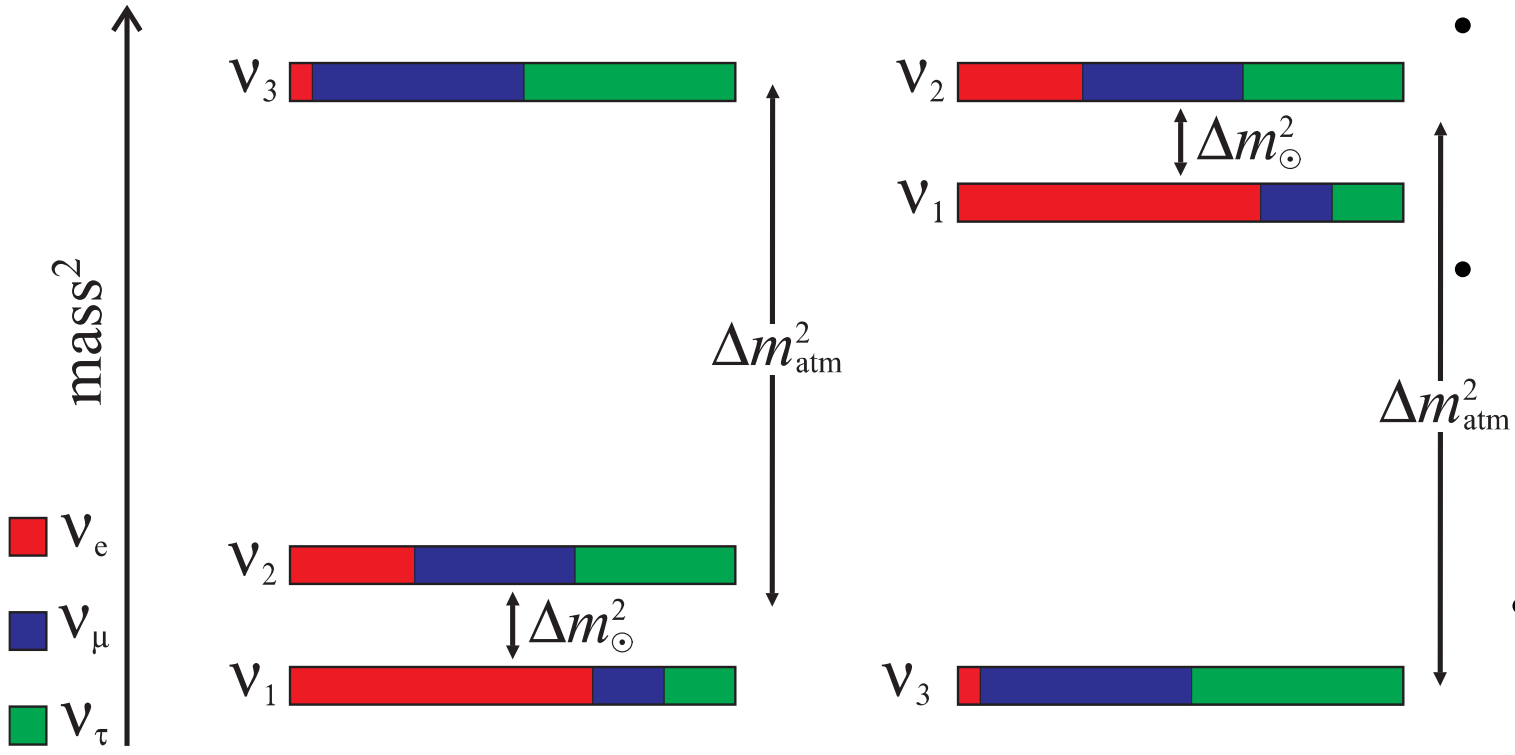
$\delta_{CP} = 1.37^{+0.18}_{-0.16}\ \pi$

PDG Prog. Theor. Exp. Phys **2020** 083C01 (2020)

Mass Squared Differences and Hierarchy

Neutrino oscillation experiments can access the mass squared differences:

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ eV^2$ $\quad$ $|\Delta m^2_{32}| = (2.453 \pm 0.034) \times 10^{-3}\ eV^2$



- By convention we denote the mass eigenstate with the largest fraction of ν_e as ν_1
- We haven't determined which mass eigenstate is the lightest → "hierarchy"
  - Normal: ν_1 is the lightest
  - Inverted: ν_3 is the lightest

PDG Prog. Theor. Exp. Phys **2020** 083C01 (2020)

PMNS Physics Goals for Long-Baseline Experiments

- What is the neutrino mass hierarchy?
- Is there a ν_μ-ν_τ symmetry?
  - Is the large mixing angle maximal, and if not, what is the octant?
- Is CP violated in the lepton sector?

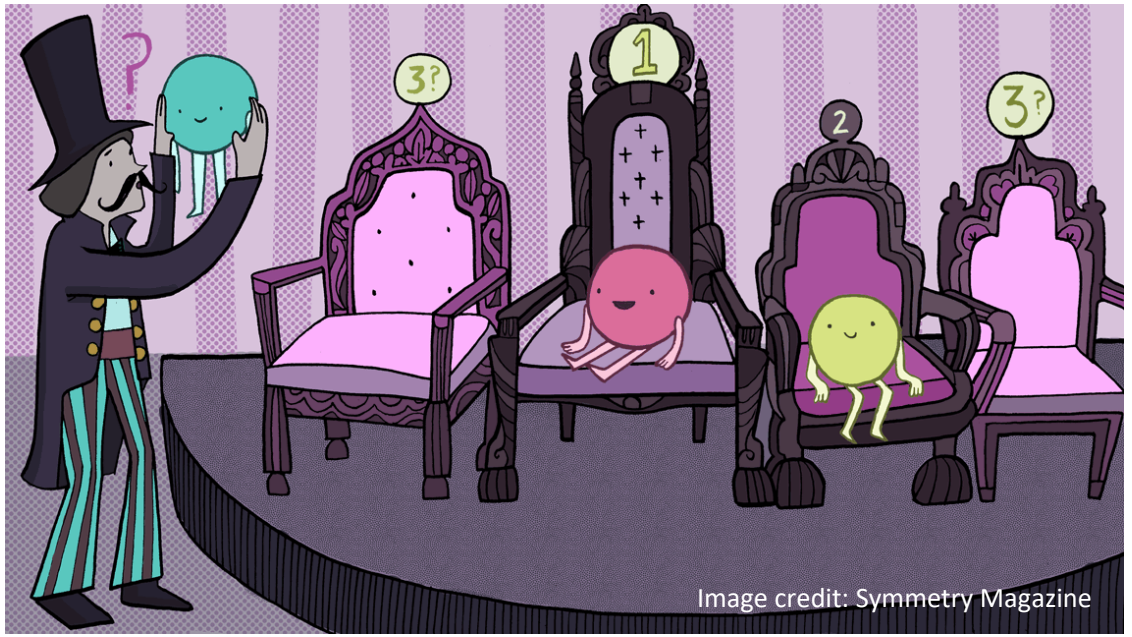
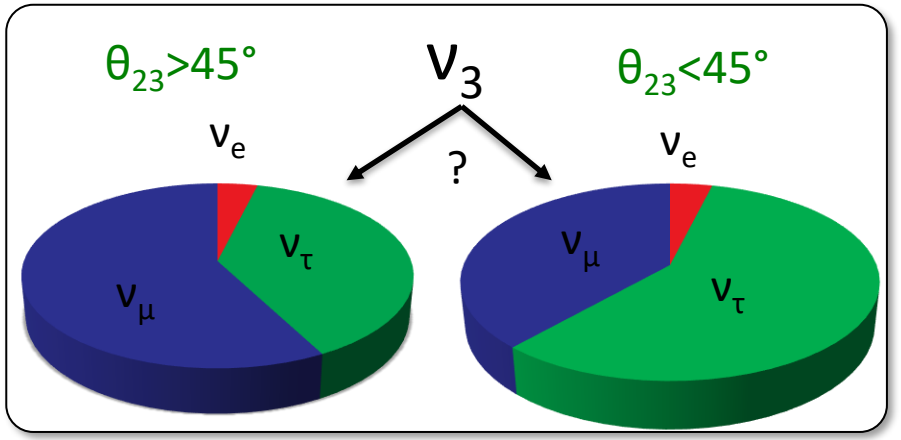
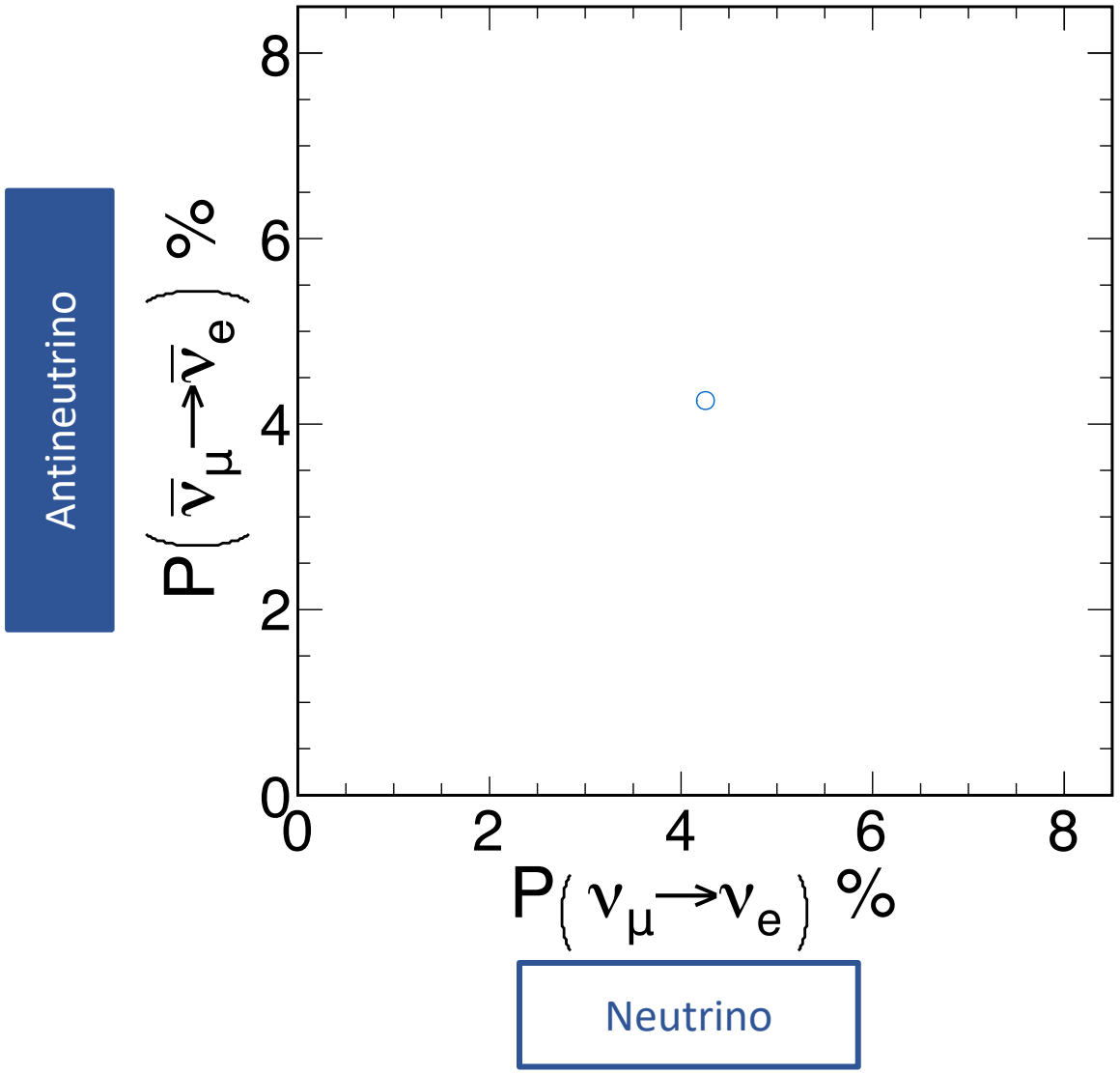


Image credit: Symmetry Magazine

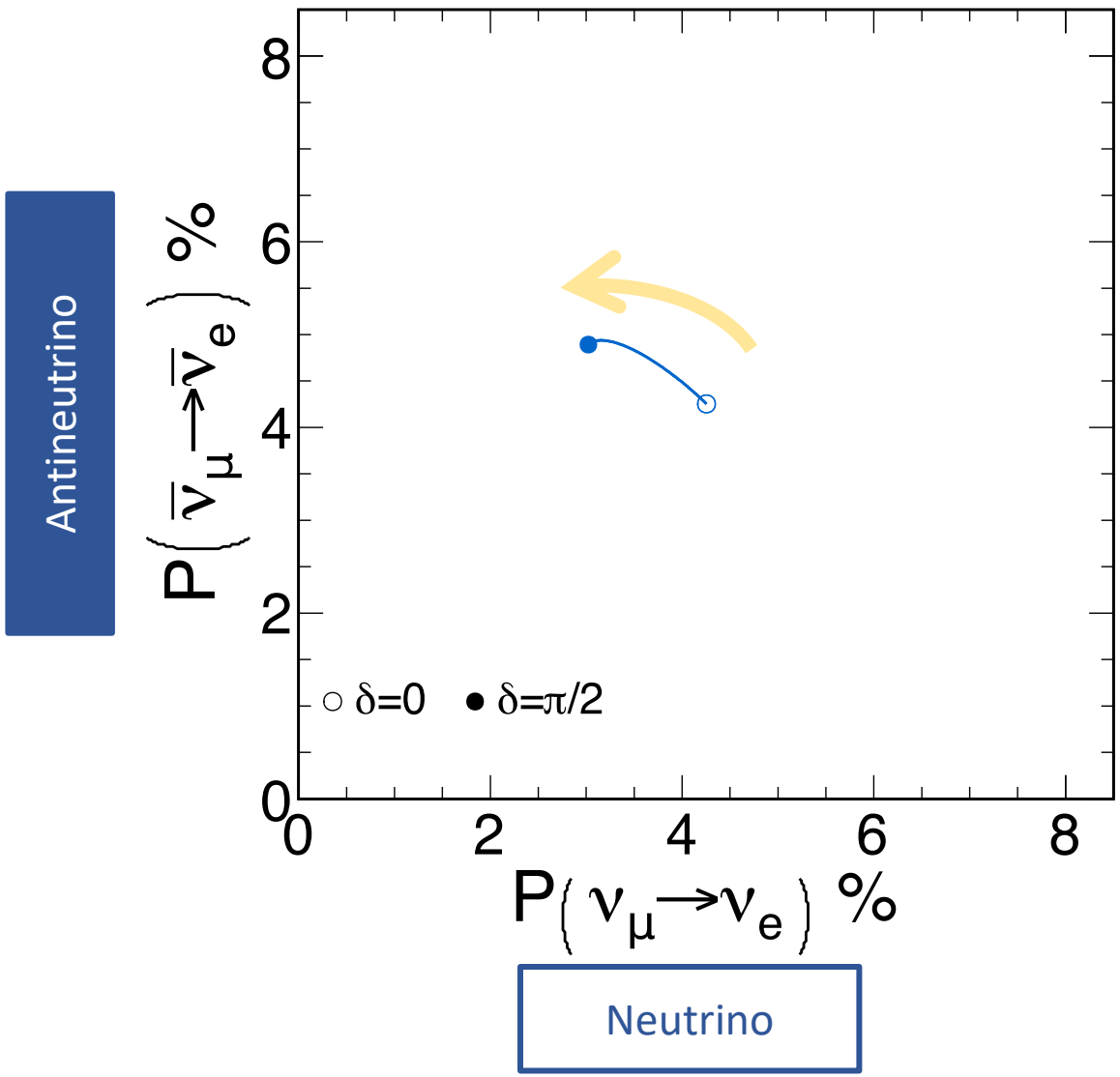


Electron Neutrino vs Antineutrino Appearance



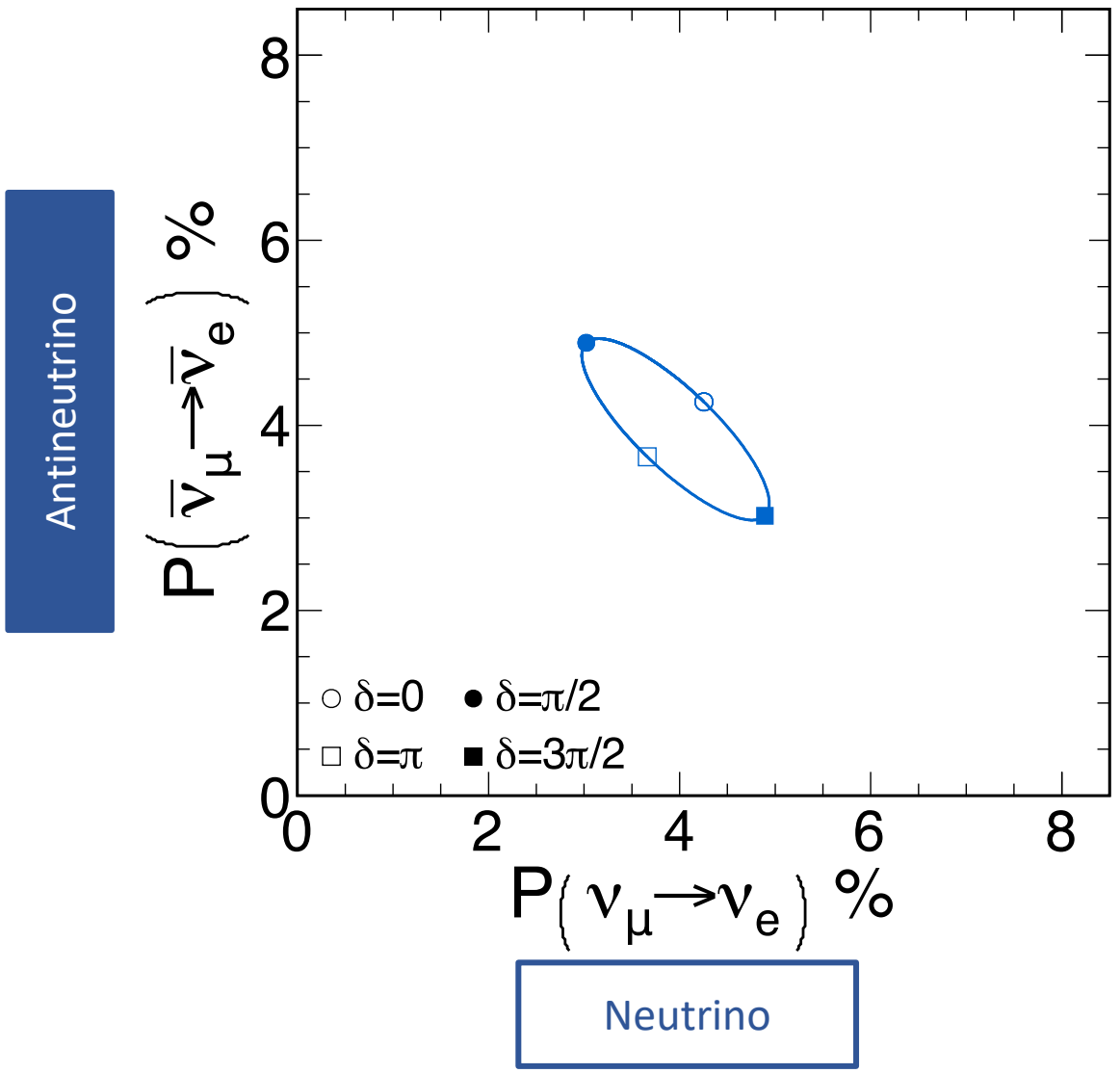
Vacuum and no CP violation: neutrinos and antineutrinos are the same

Electron Neutrino vs Antineutrino Appearance



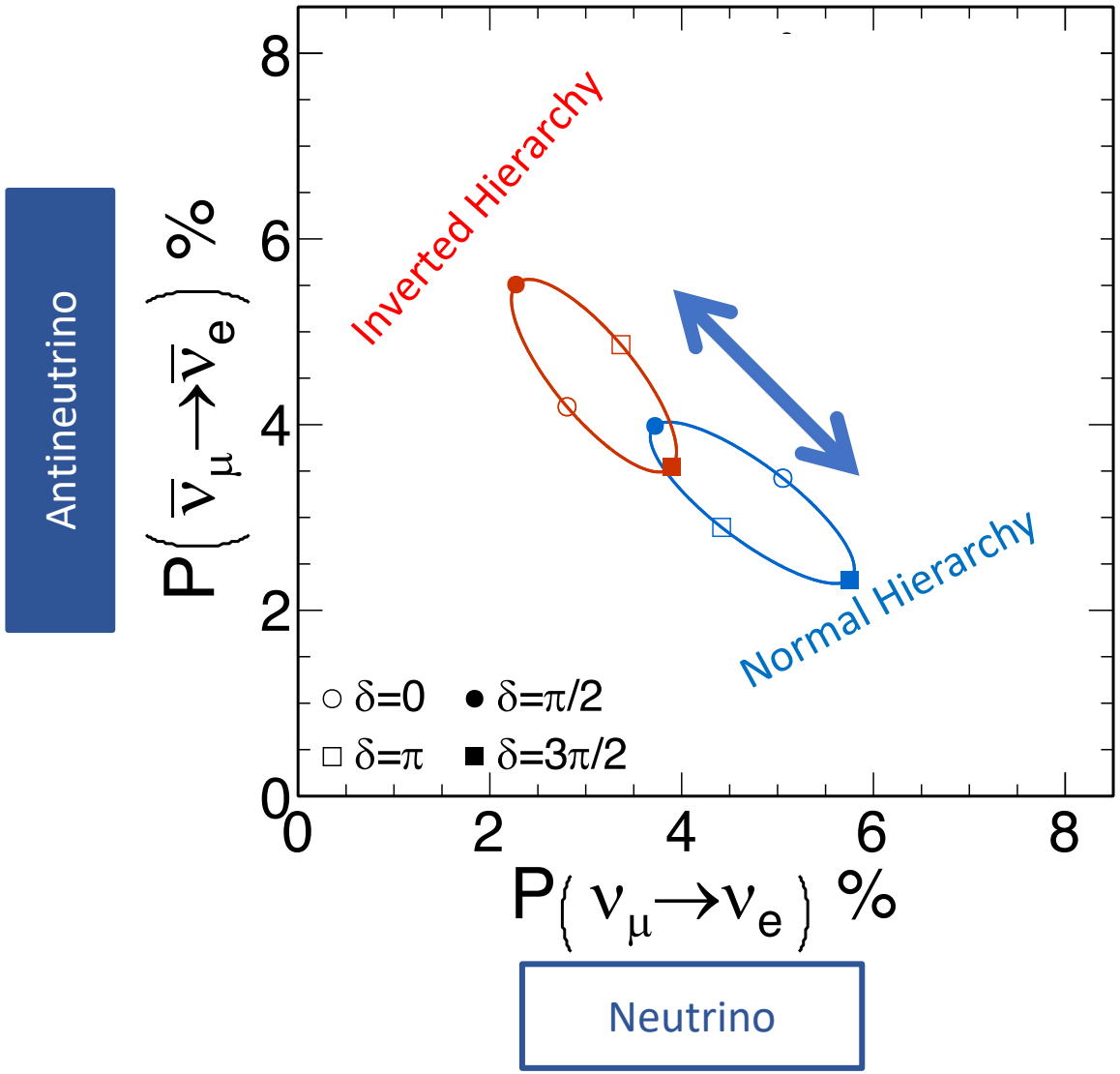
CP-violation through δ creates opposite effects in neutrinos and antineutrinos

Electron Neutrino vs Antineutrino Appearance



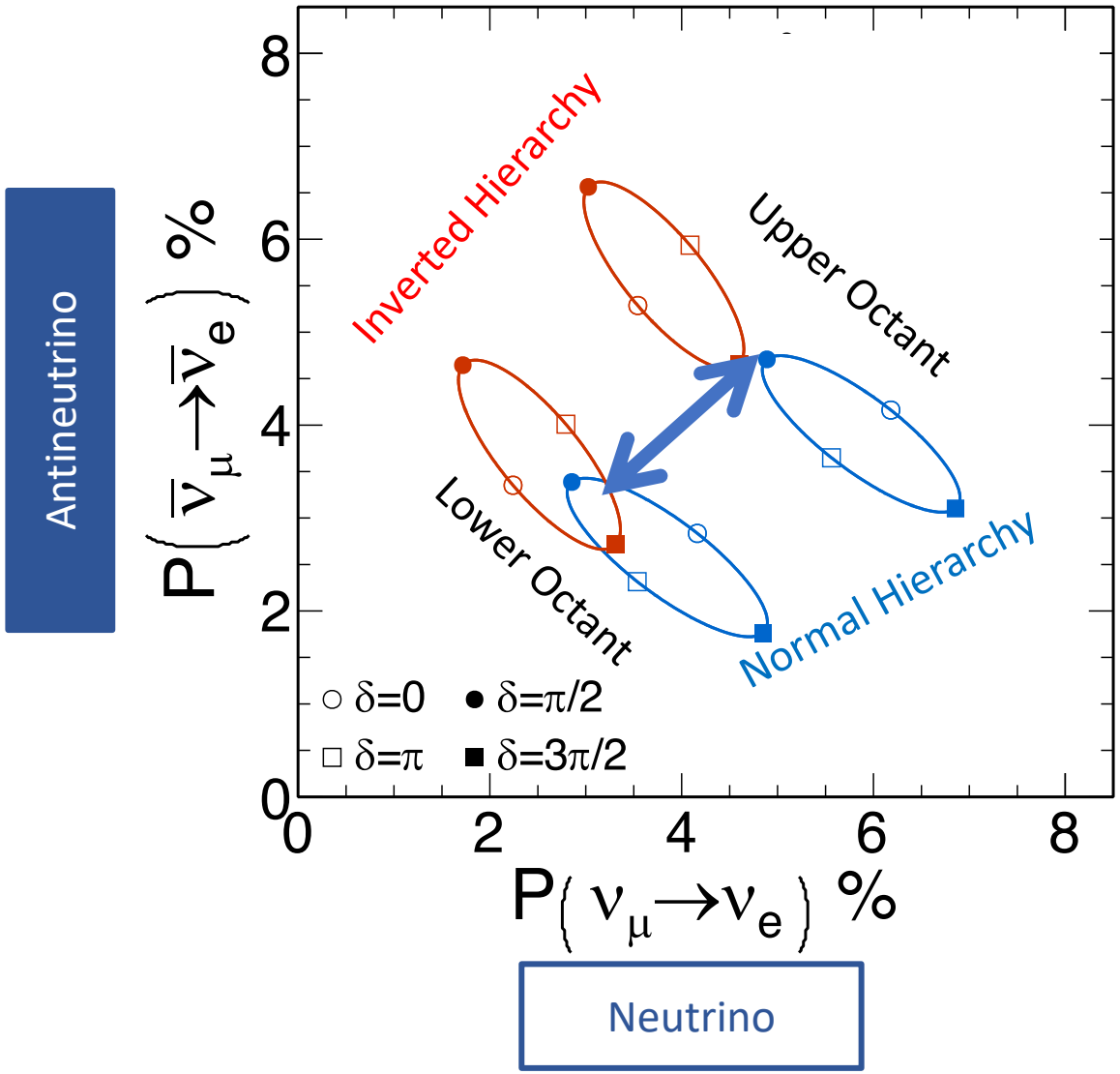
CP-violation through δ creates opposite effects in neutrinos and antineutrinos

Electron Neutrino vs Antineutrino Appearance



Matter effects also introduce opposite neutrino-antineutrino effects.

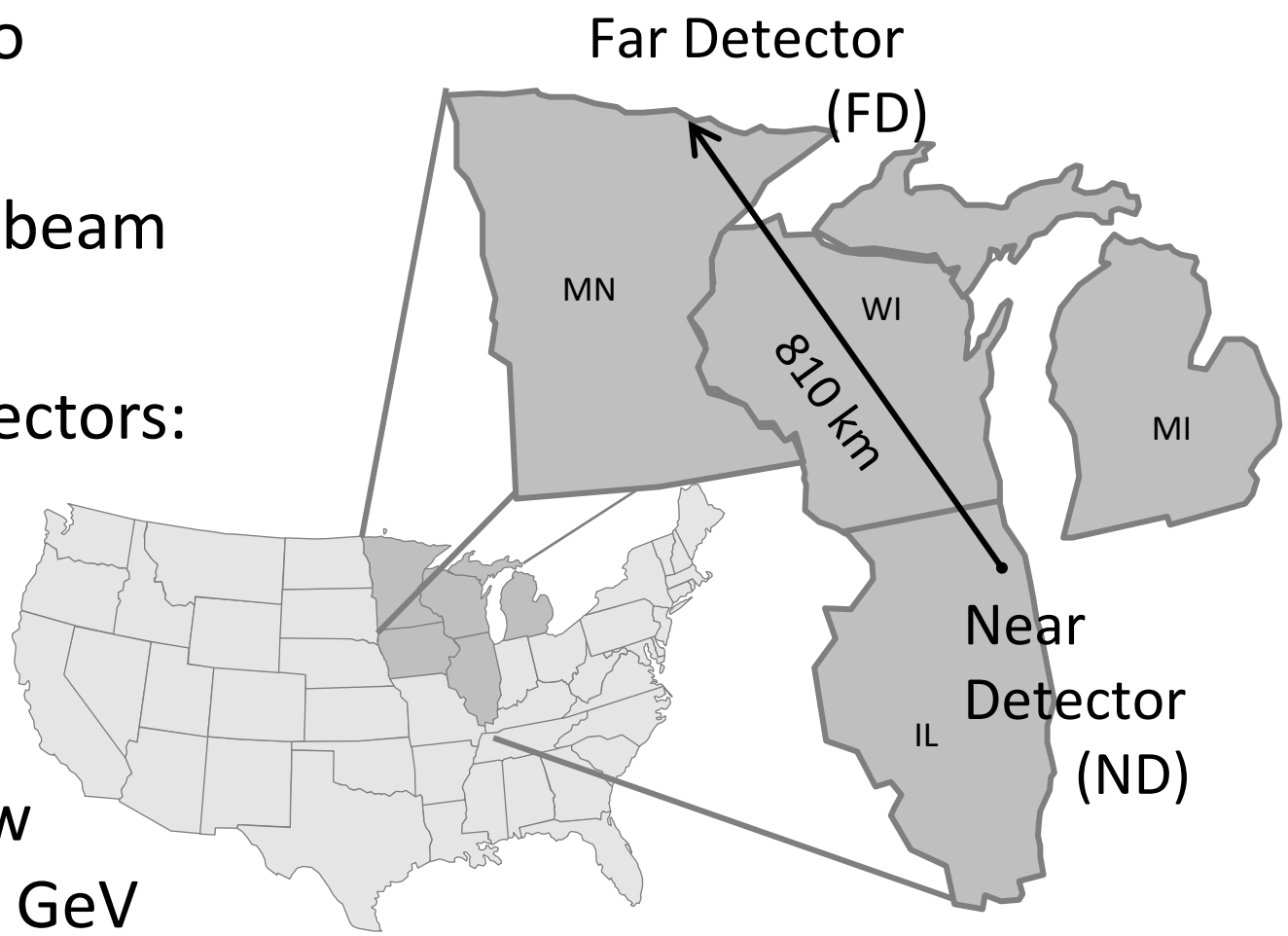
Electron Neutrino vs Antineutrino Appearance



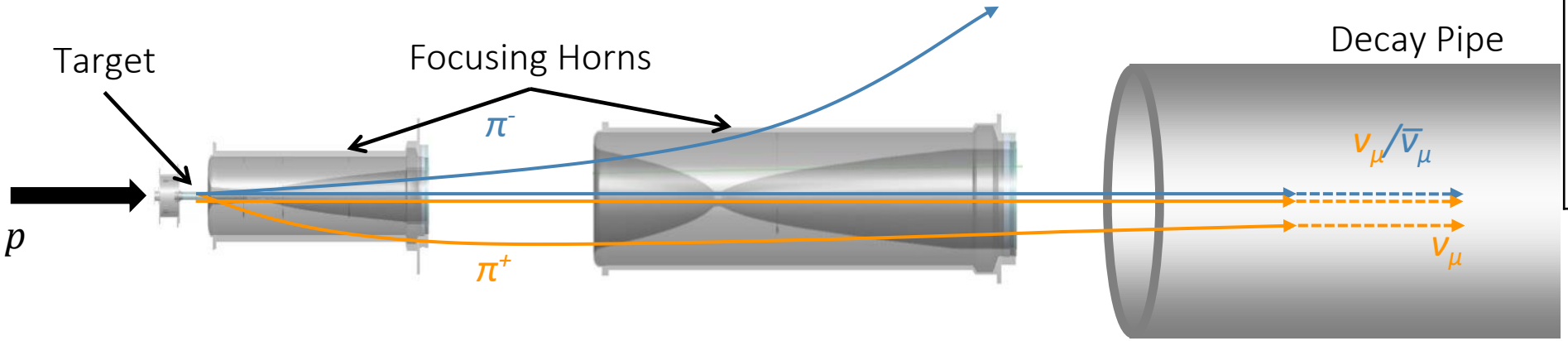
The octant creates the same effect in neutrinos and antineutrinos.

NOvA

- NOvA is a long-baseline neutrino oscillation experiment
- Study neutrinos from the NuMI beam at Fermilab
- Two functionally equivalent detectors:
  - Far Detector (FD)
    14 kton; on the surface
  - Near Detector (ND)
    0.3 kton; underground
- Off axis position provides narrow band beam that peaks around 2 GeV



NuMI Neutrino Beam

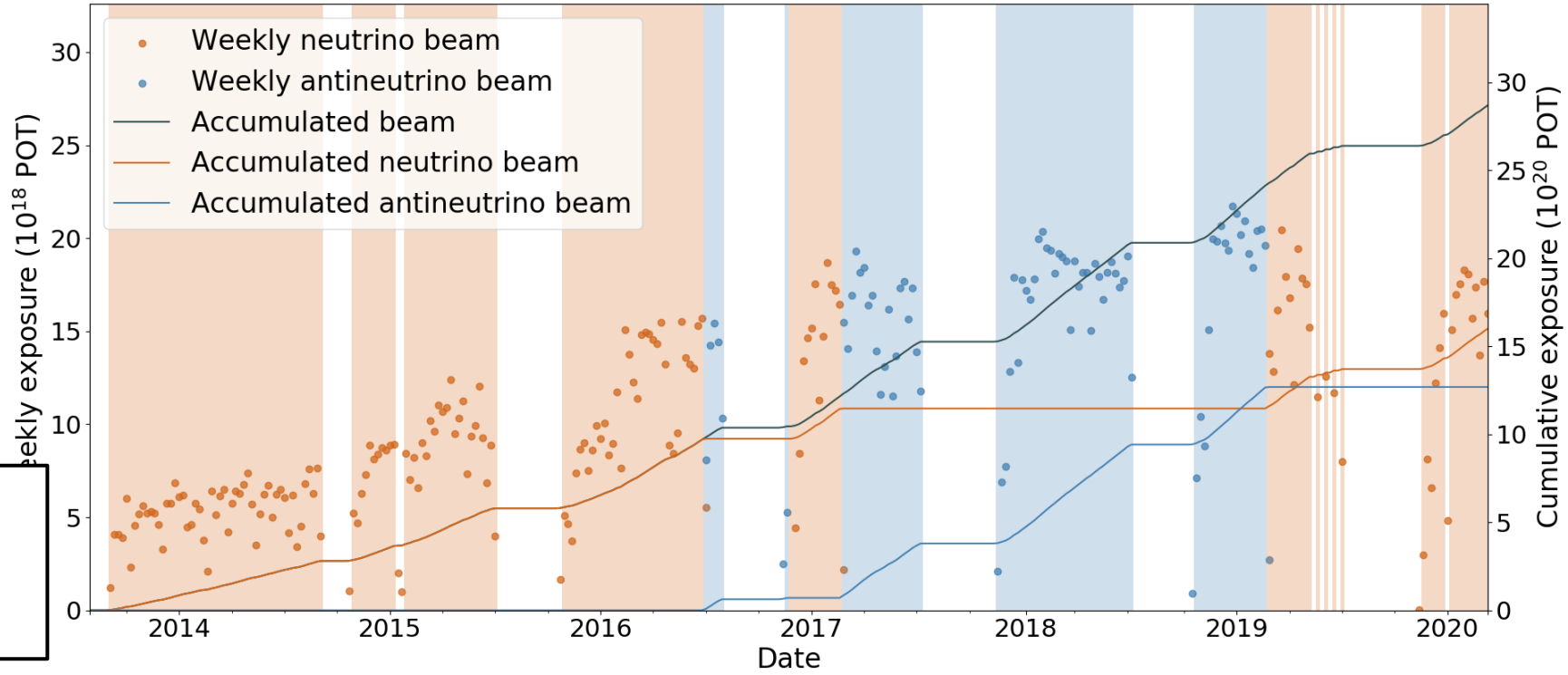


Flux 1-5 GeV

95% ν_μ

4% $\bar{\nu}_\mu$

1% ν_e

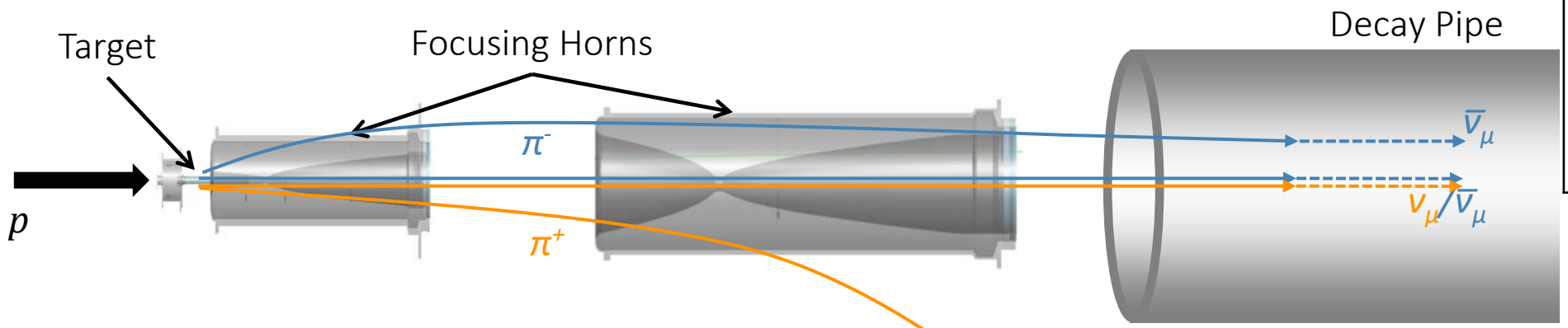


Exposure (POT)

ν: 13.6 x 10^{20}

$\bar{\nu}$: 12.5 x 10^{20}

NuMI Antineutrino beam

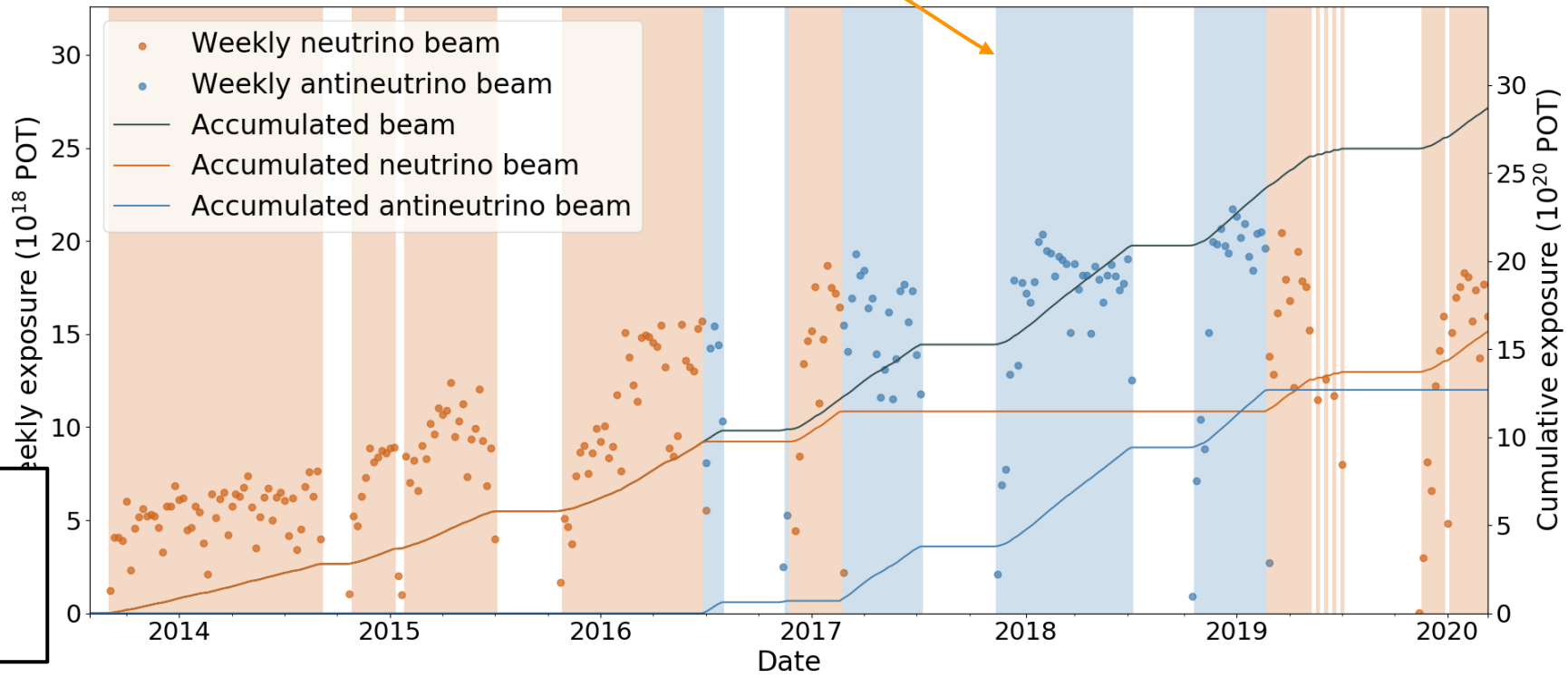


Flux 1-5 GeV

6% ν_μ

93% $\bar{\nu}_\mu$

1% ν_e

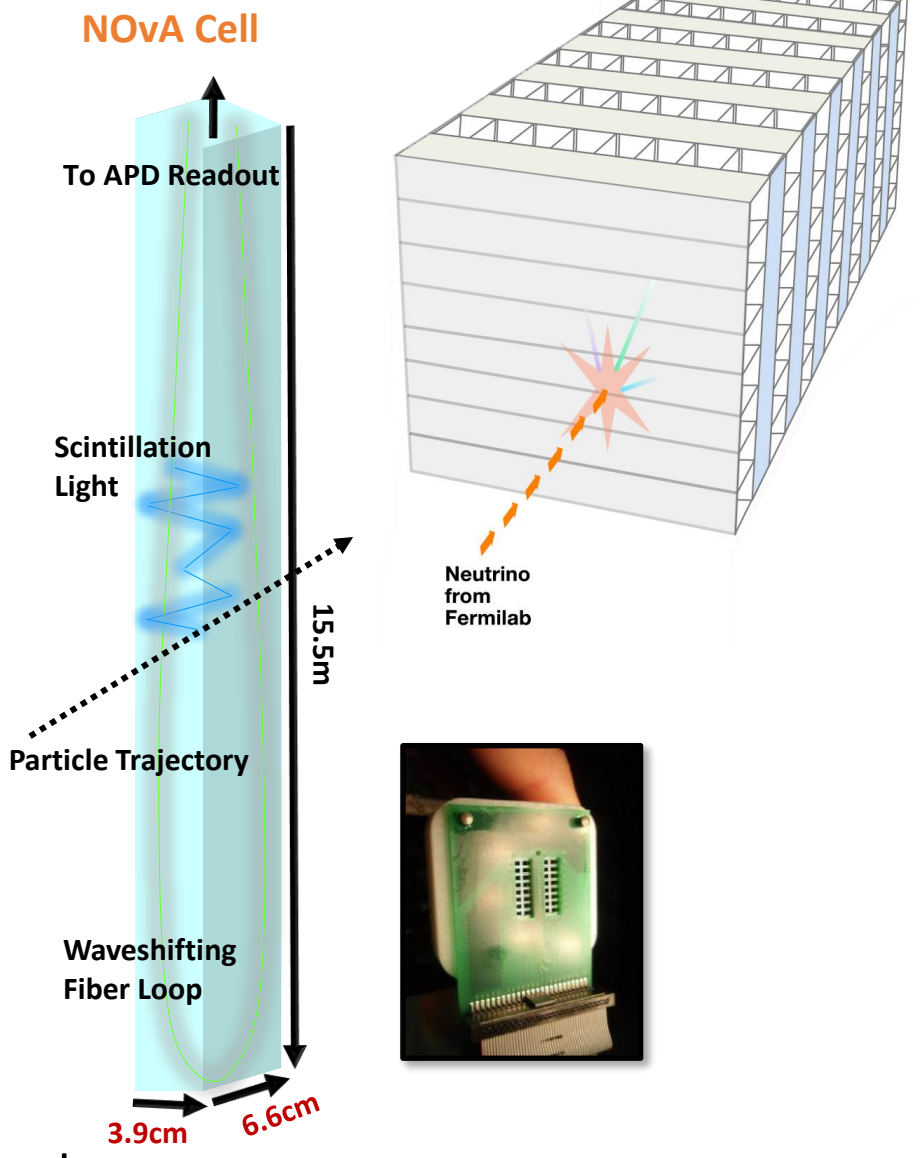


Exposure (POT)

ν: 13.6 x 10^{20}

$\bar{\nu}$: 12.5 x 10^{20}

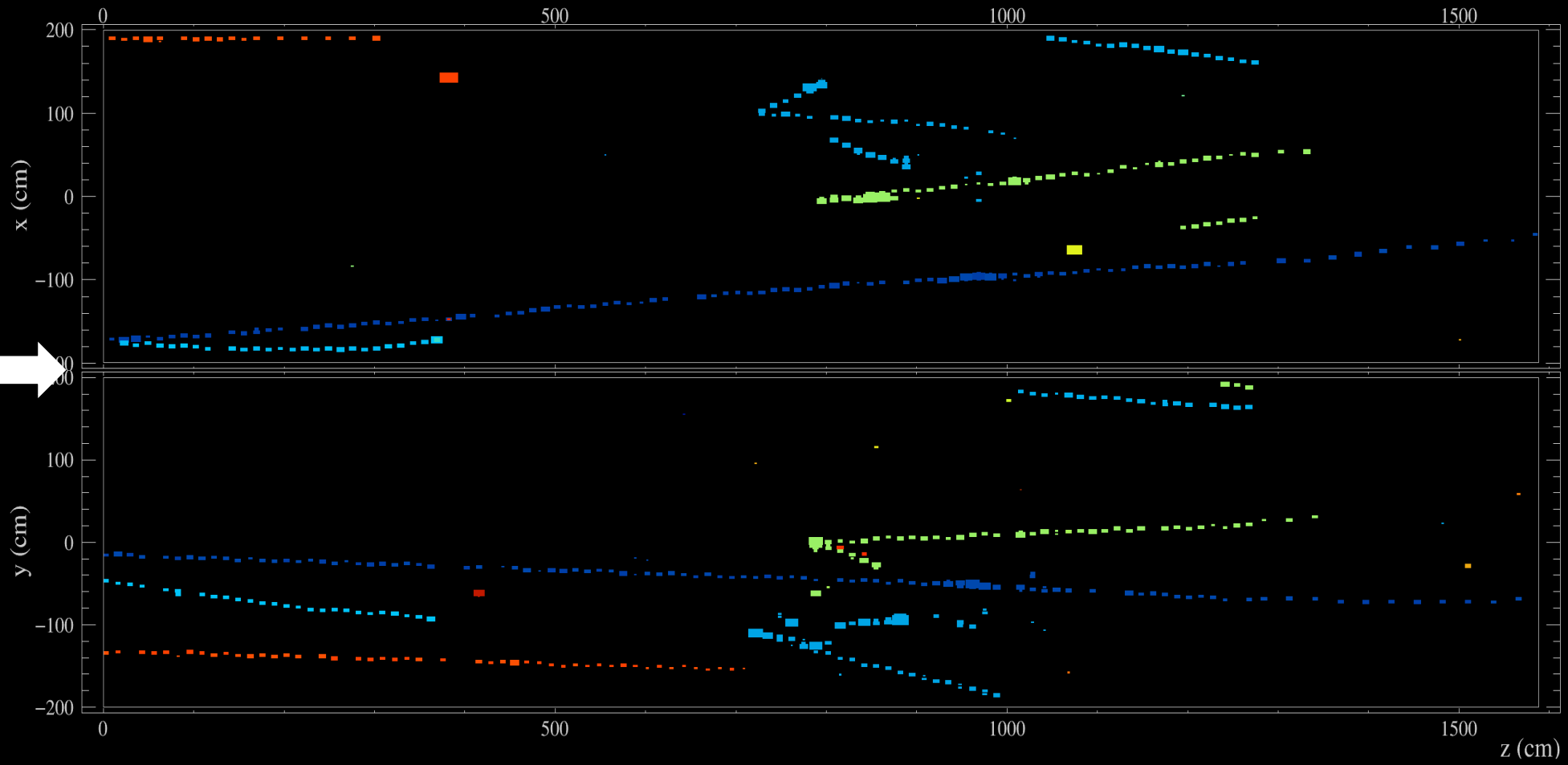
NOvA Detectors

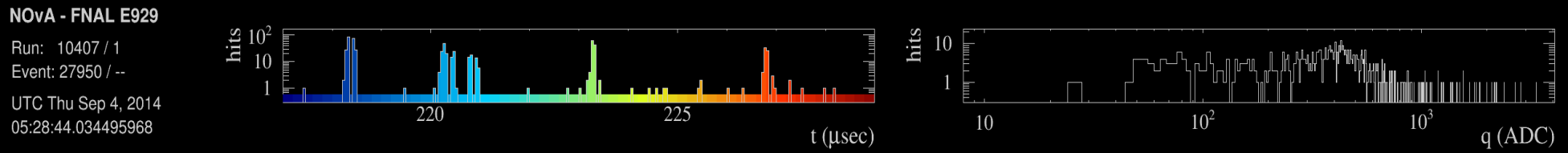


- Detectors are optimized for electron showers
  - Fine-grained, low-*Z*, highly-active tracking calorimeters
- Cells are PVC, filled with liquid scintillator
- Read out via wavelength shifting fiber to APD
- Orthogonal layers of cells → top and side view for each event

Near Detector Event Display

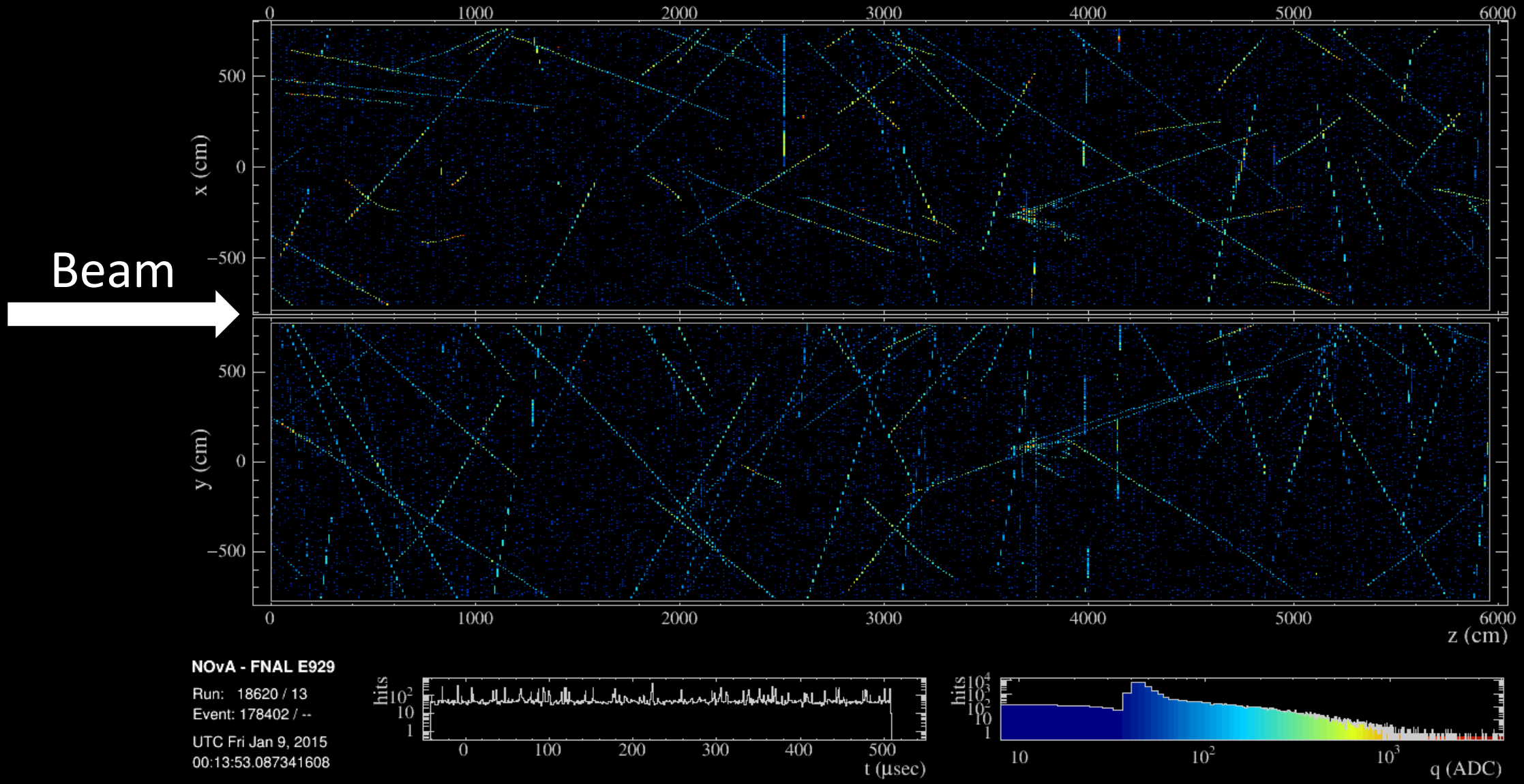
Beam





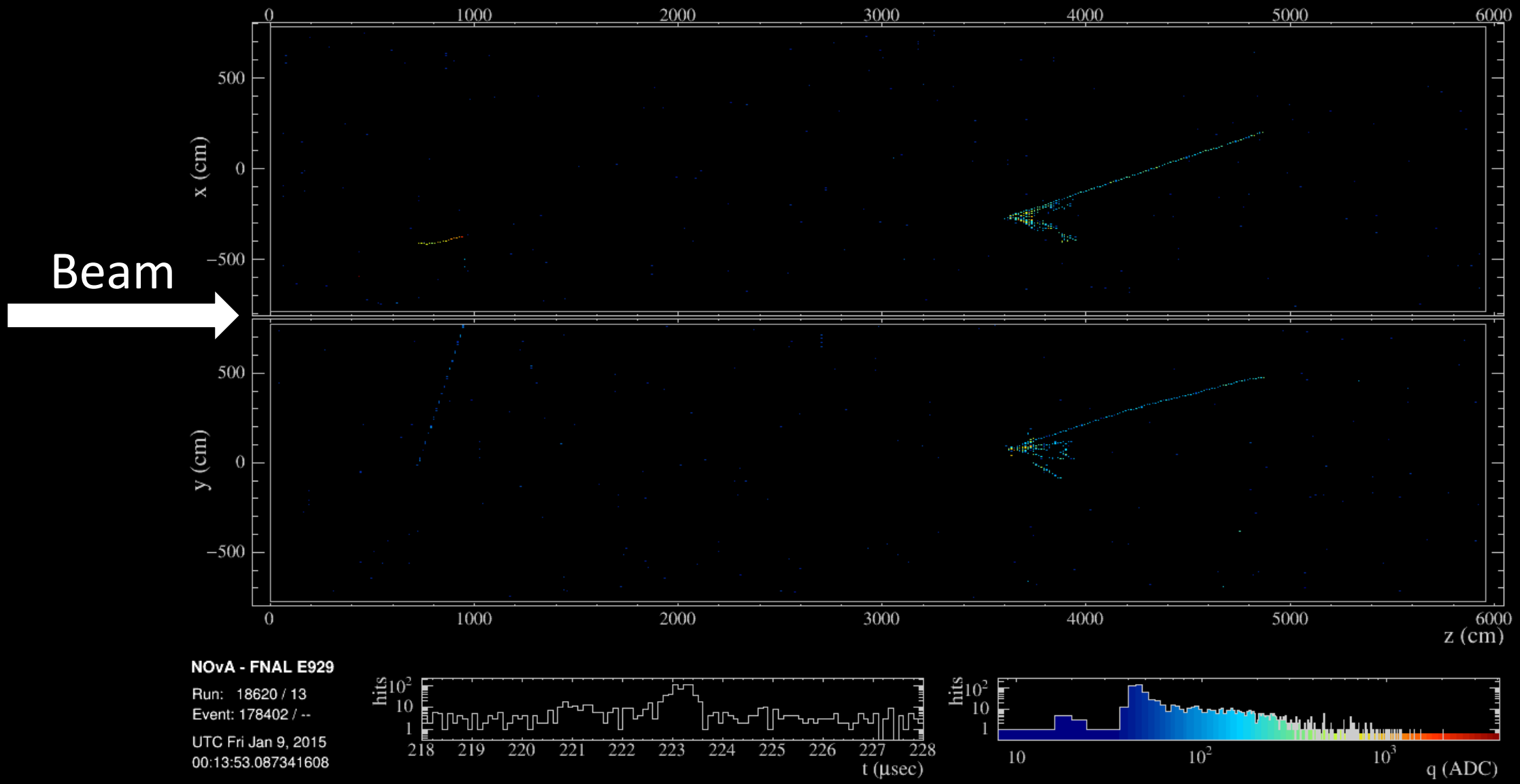
(colors show hit times)

Far Detector Event Display – 550 µs



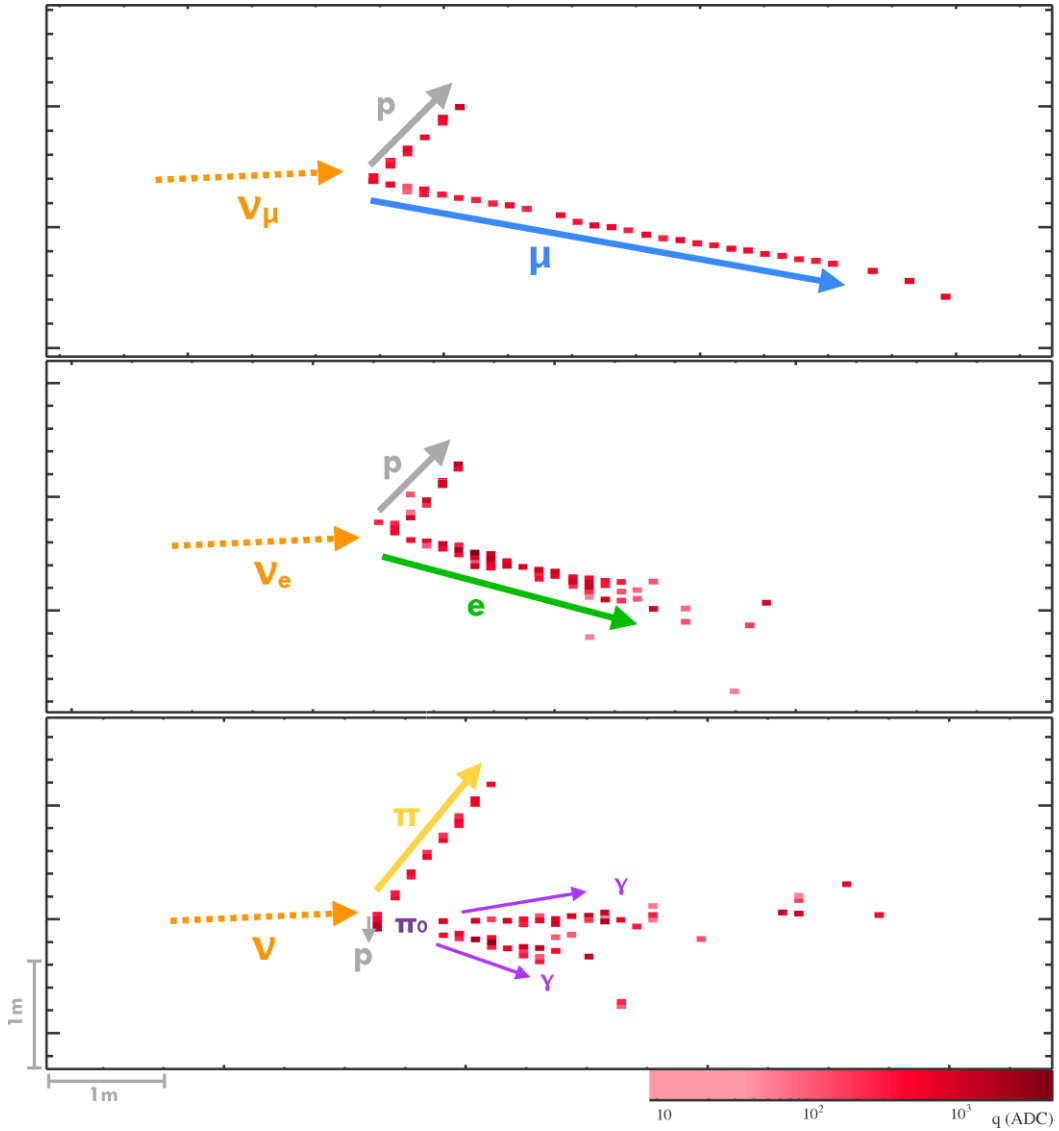
(colors show charge)

Far Detector Event Display – 10 µs



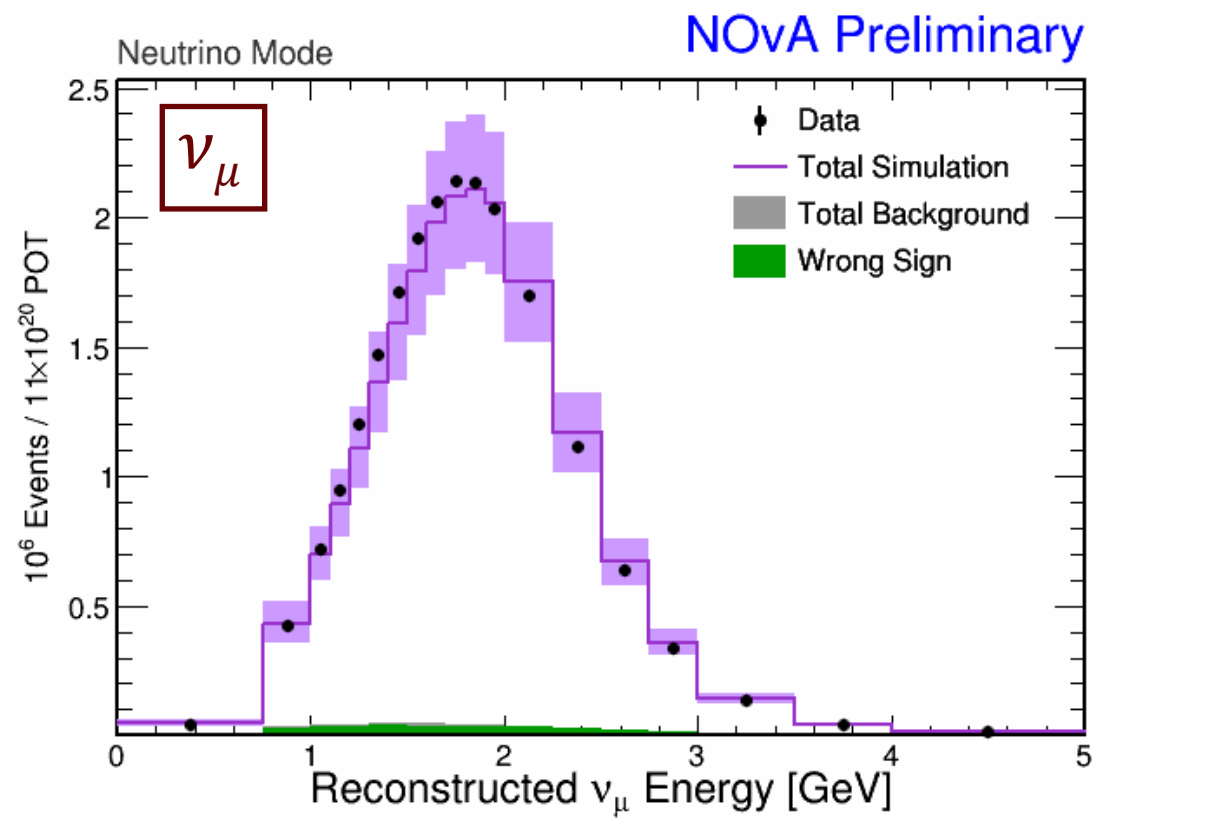
(colors show charge)

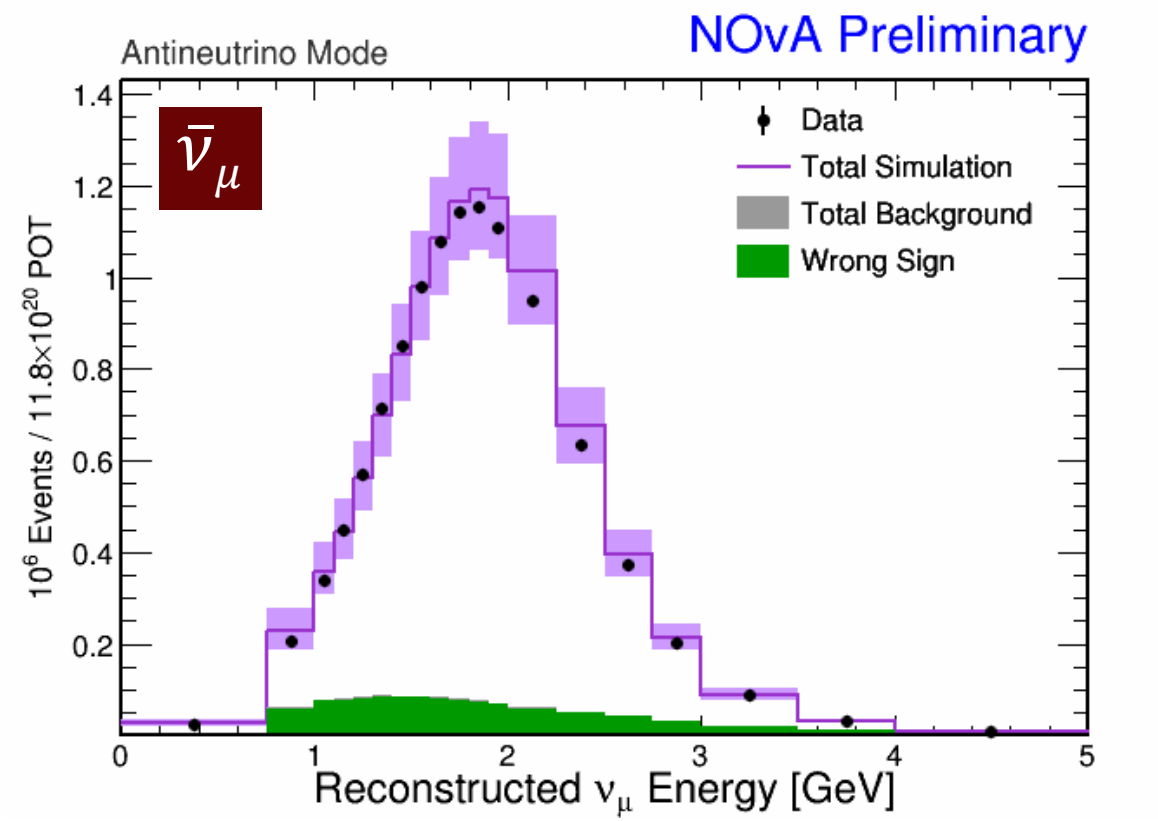
Event Identification



- Identify flavor with convolutional neural network
- Before CNN:
  - Need to be contained
  - ν_μCC needs a well reconstructed muon track
  - First pass of cosmic rejection
- Performance relative to preselection
  - ν_μ : ~90% efficient, 99% bkg rejection
  - ν_e : ~80% efficient, 80% bkg rejection

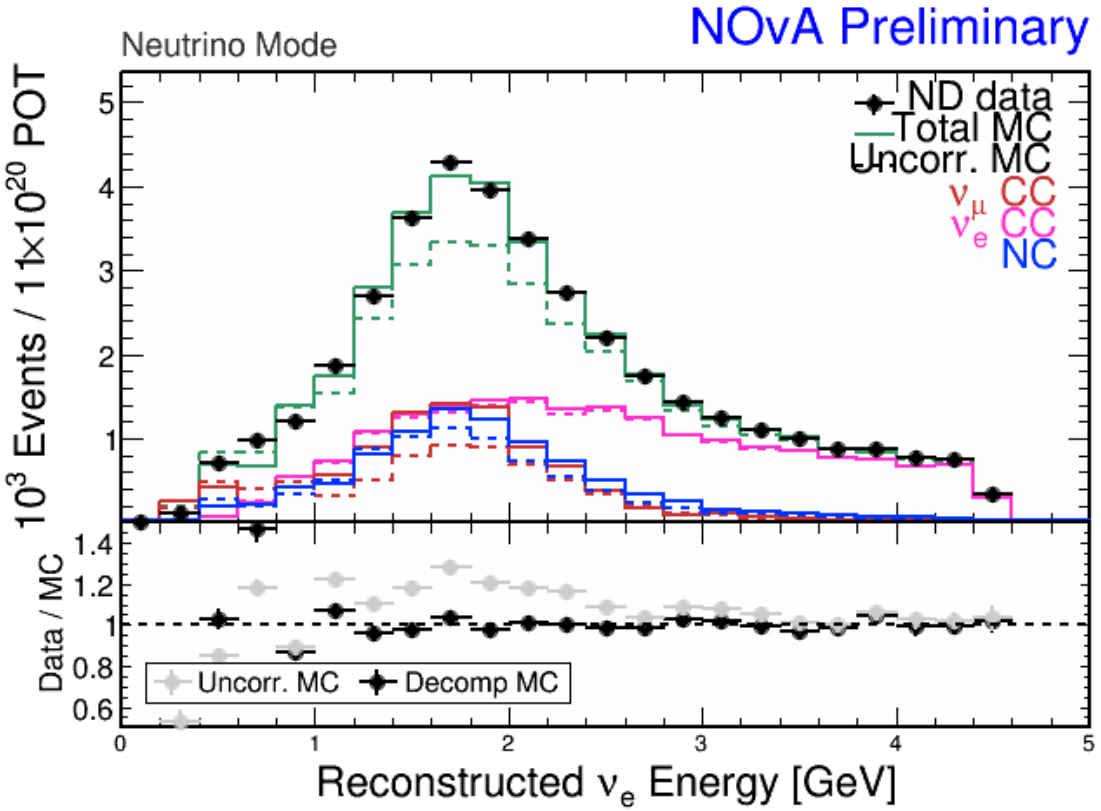
Muon Neutrinos at the ND

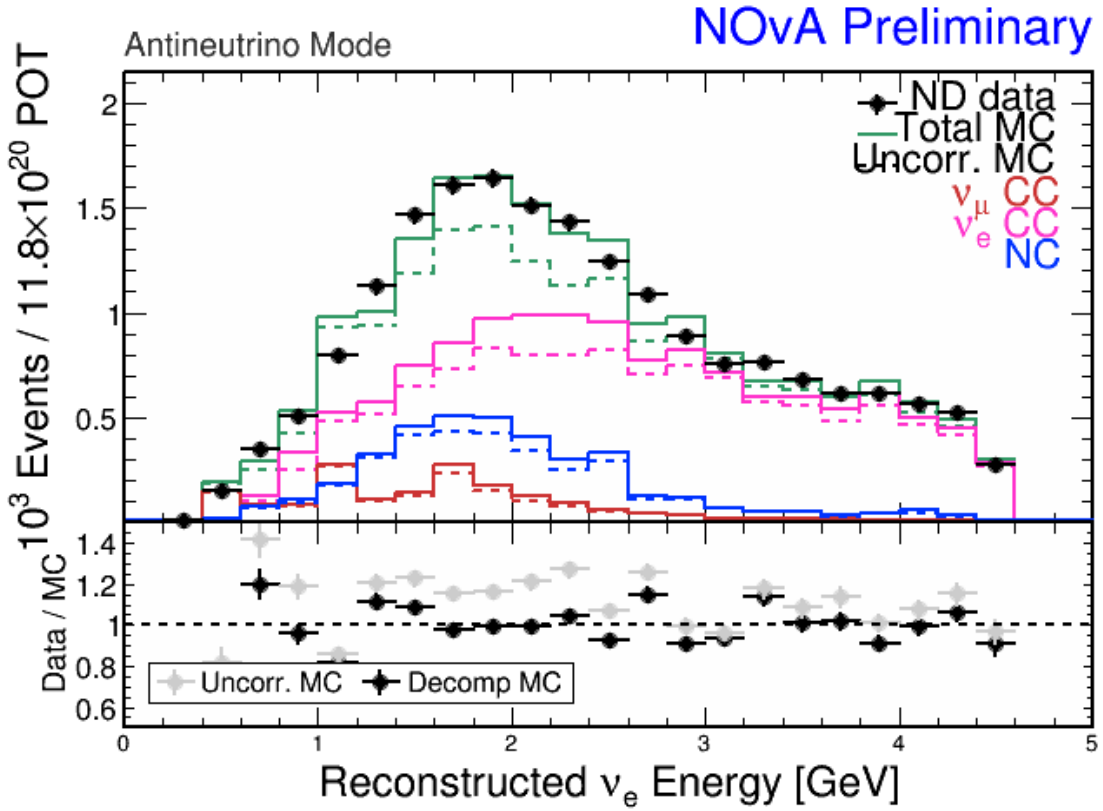




- Used to predict both ν_μ and ν_e spectra at the FD
- Large error band shows the effect of flux and cross-section uncertainties in one detector

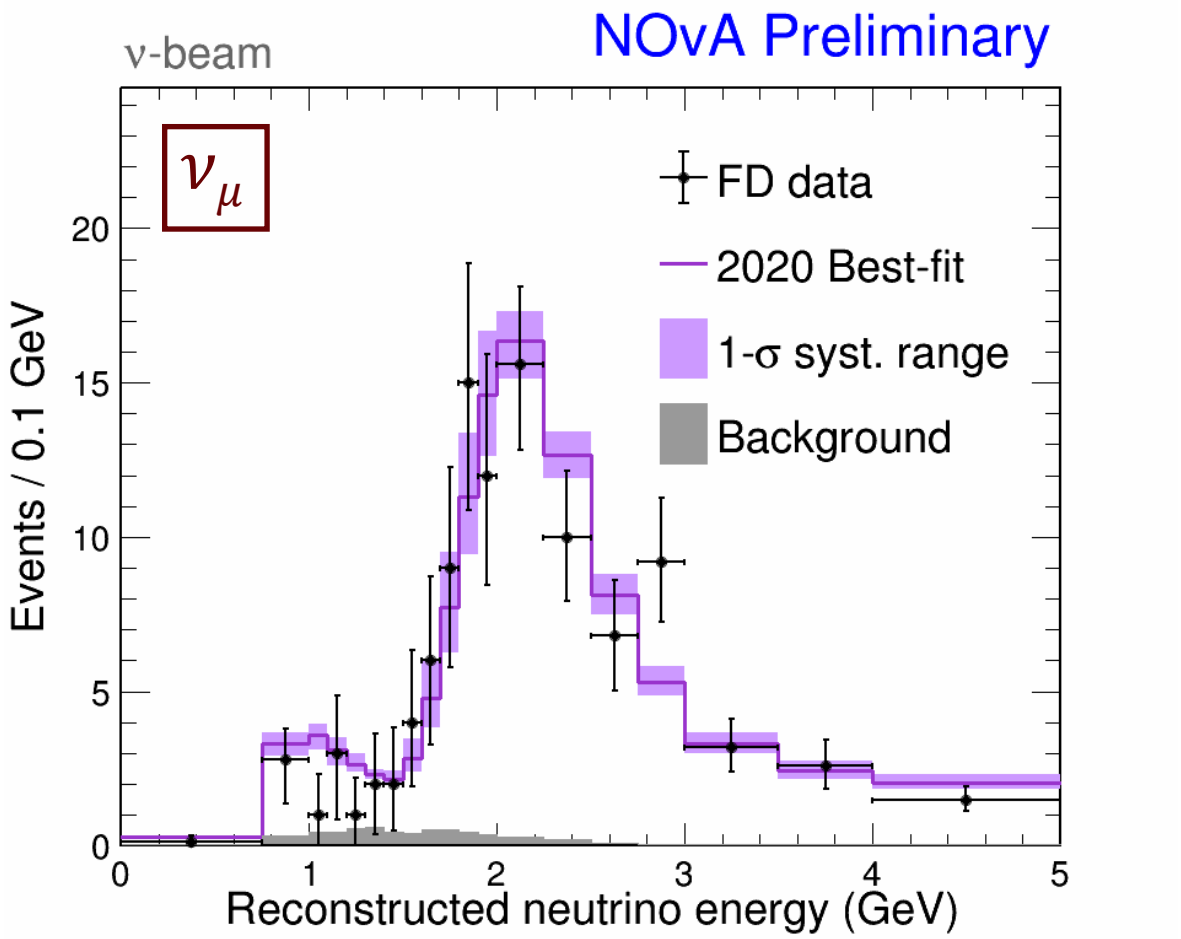
Electron Neutrinos at the ND



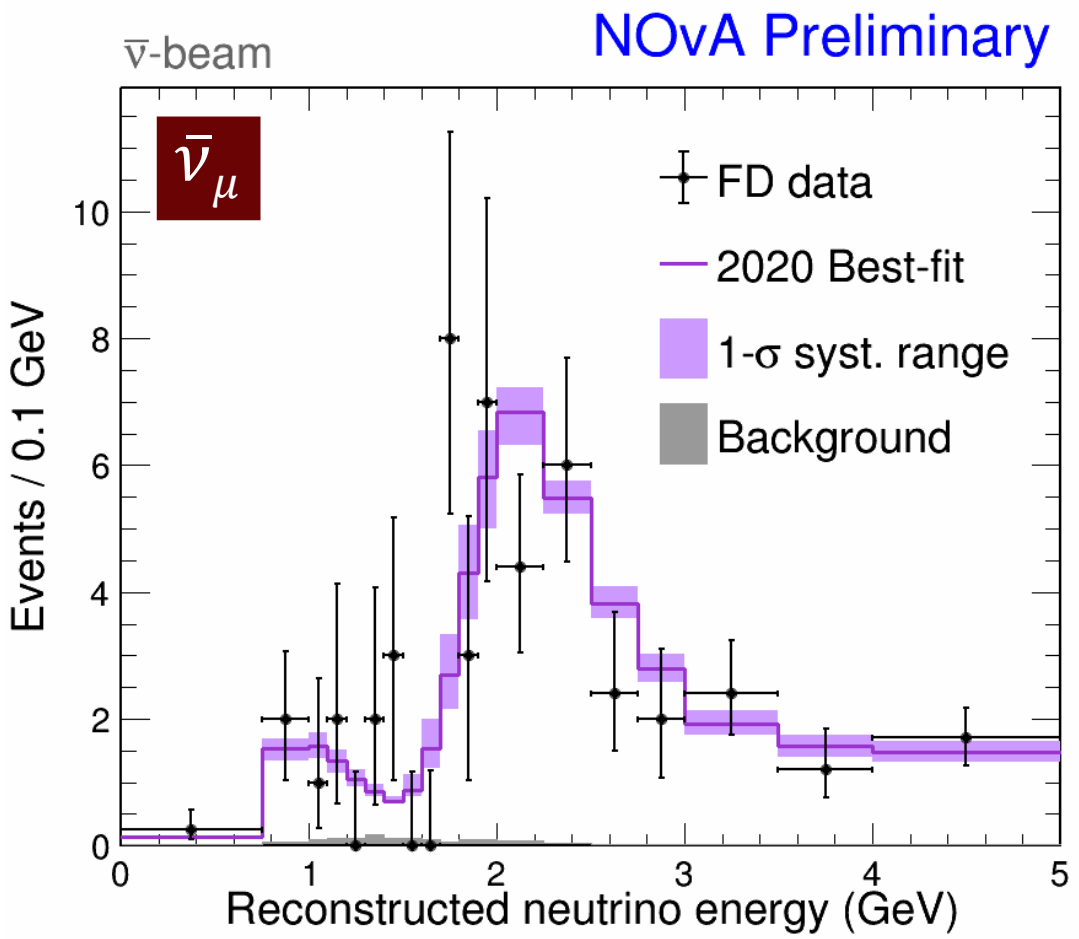


- ND ν_e-like sample has no appearance – all background
- This sample is used to predict the background at the FD
- Largest background is the irreducible beam $\nu_e/\bar{\nu}_e$

Muon Neutrinos at the FD

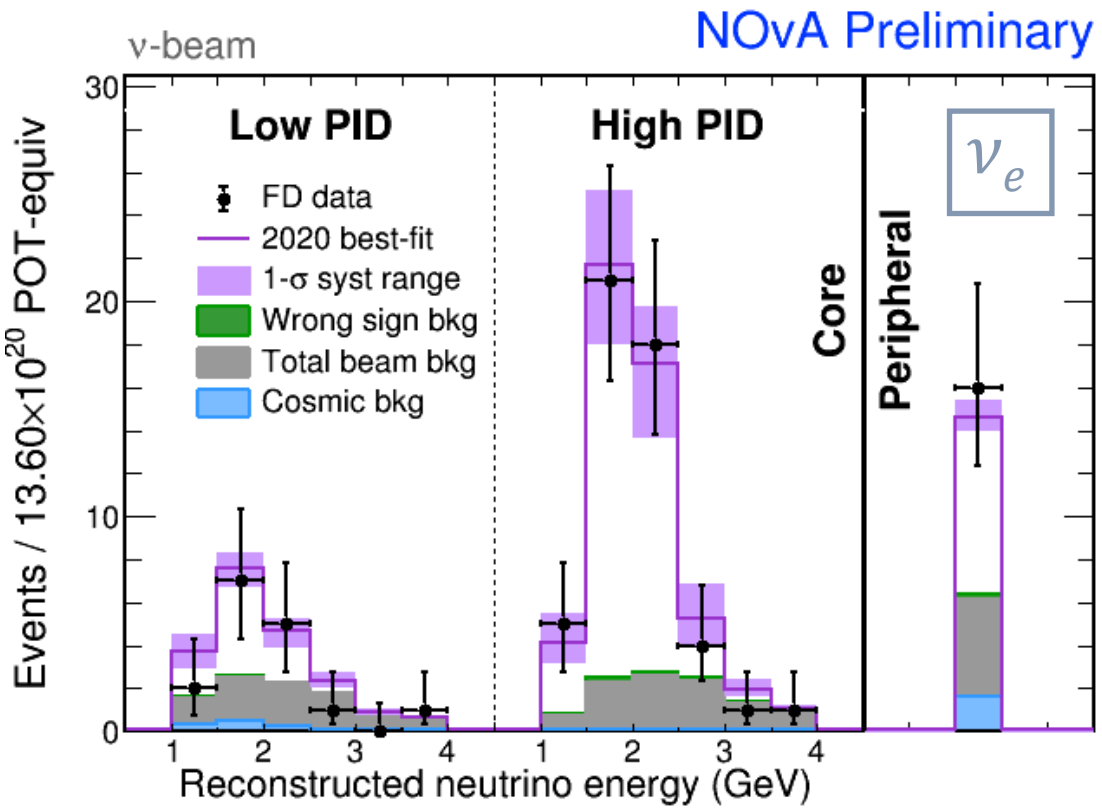


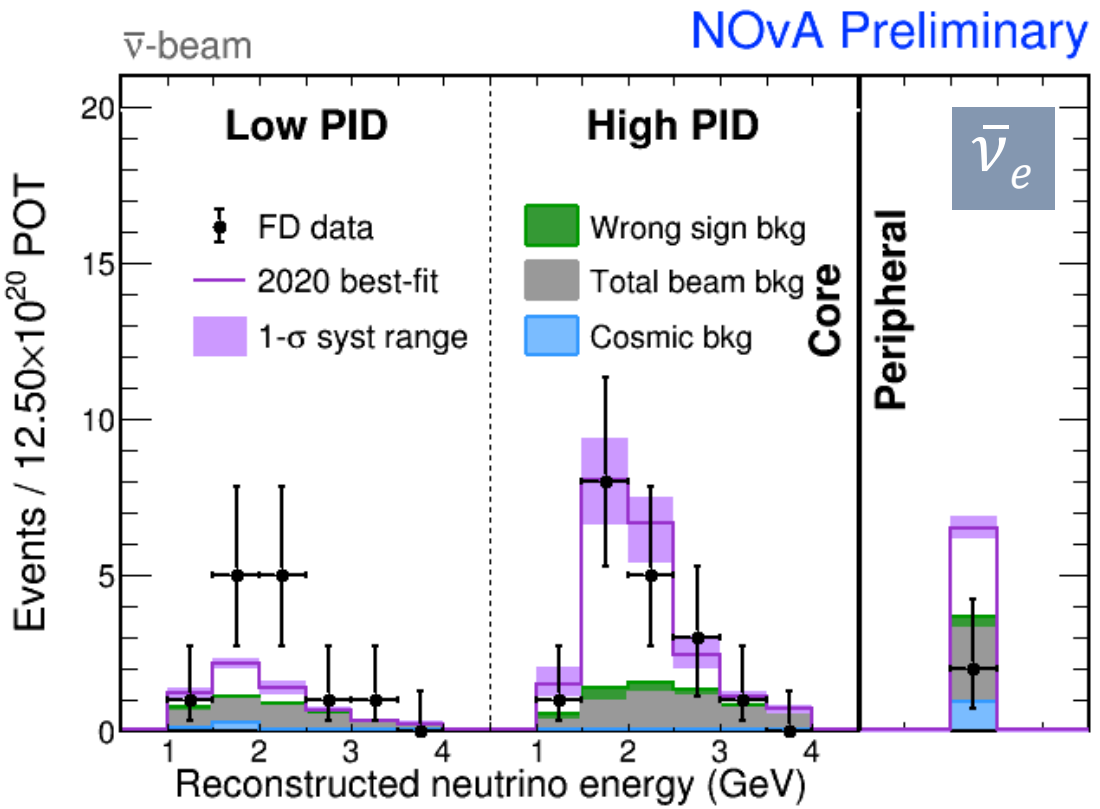
211 events, 8.2 background



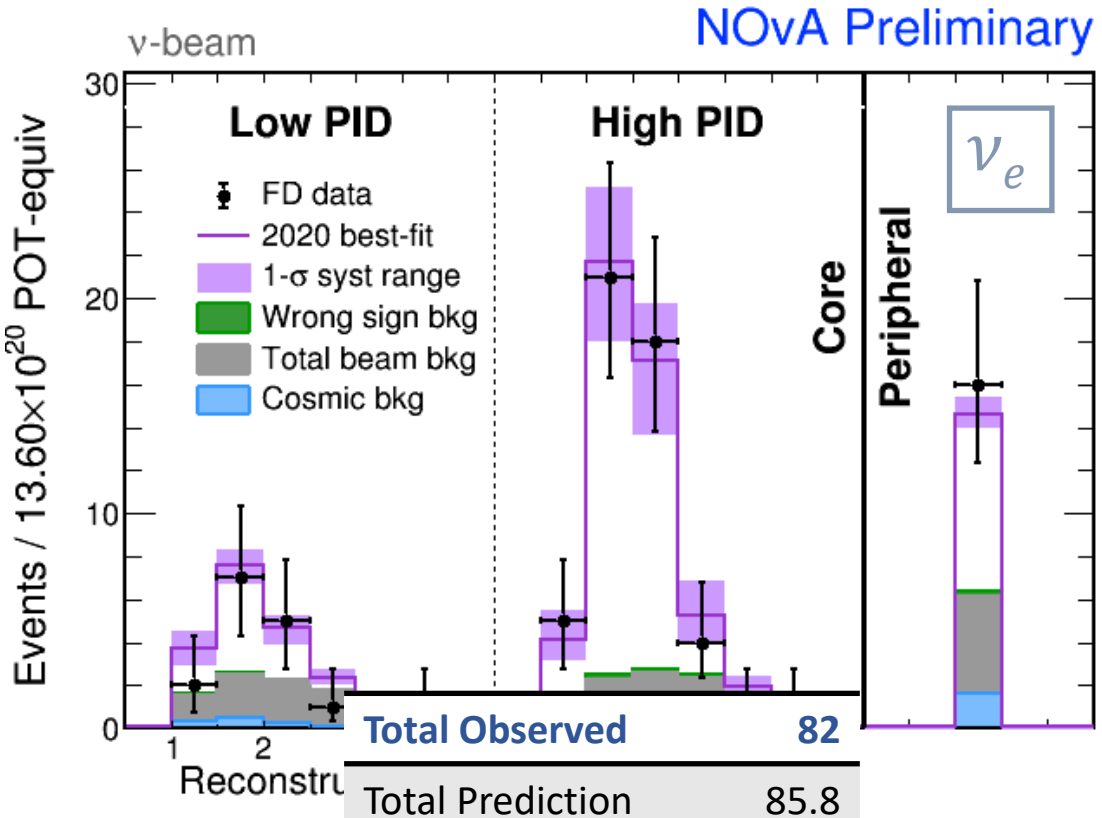
105 events, 2.1 background

Electron Neutrinos at the FD

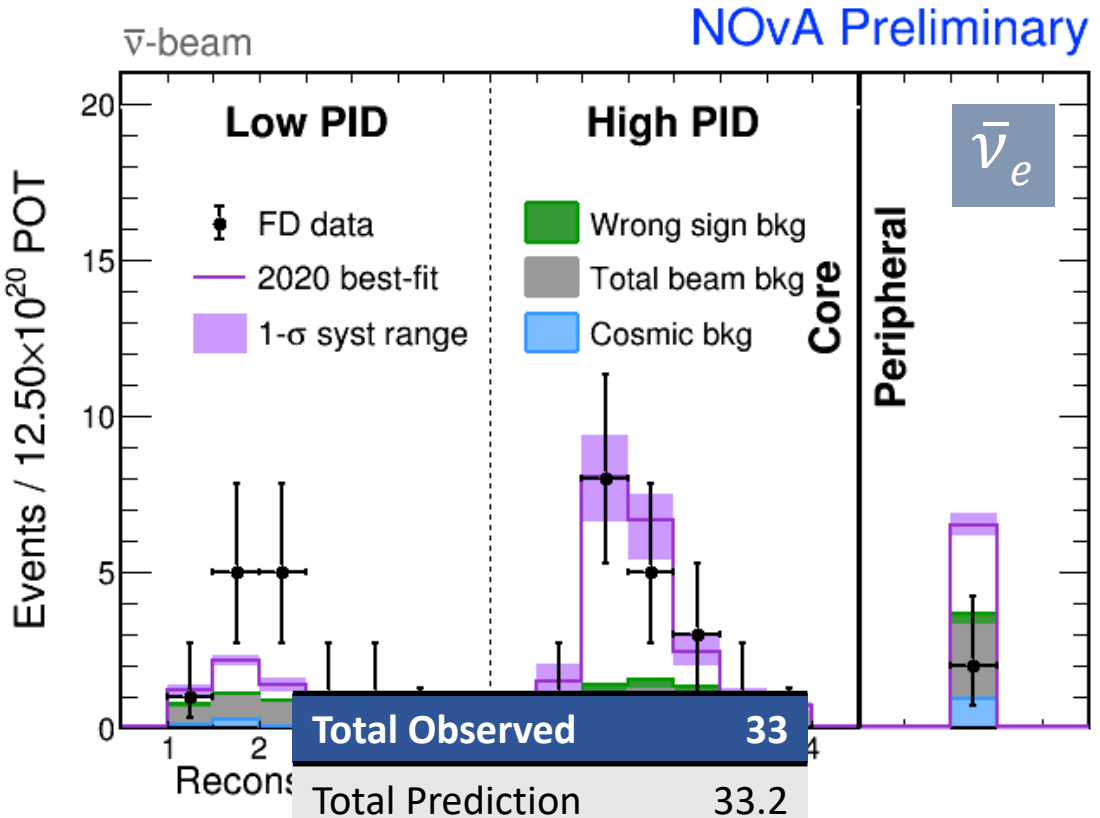




Electron Neutrinos at the FD



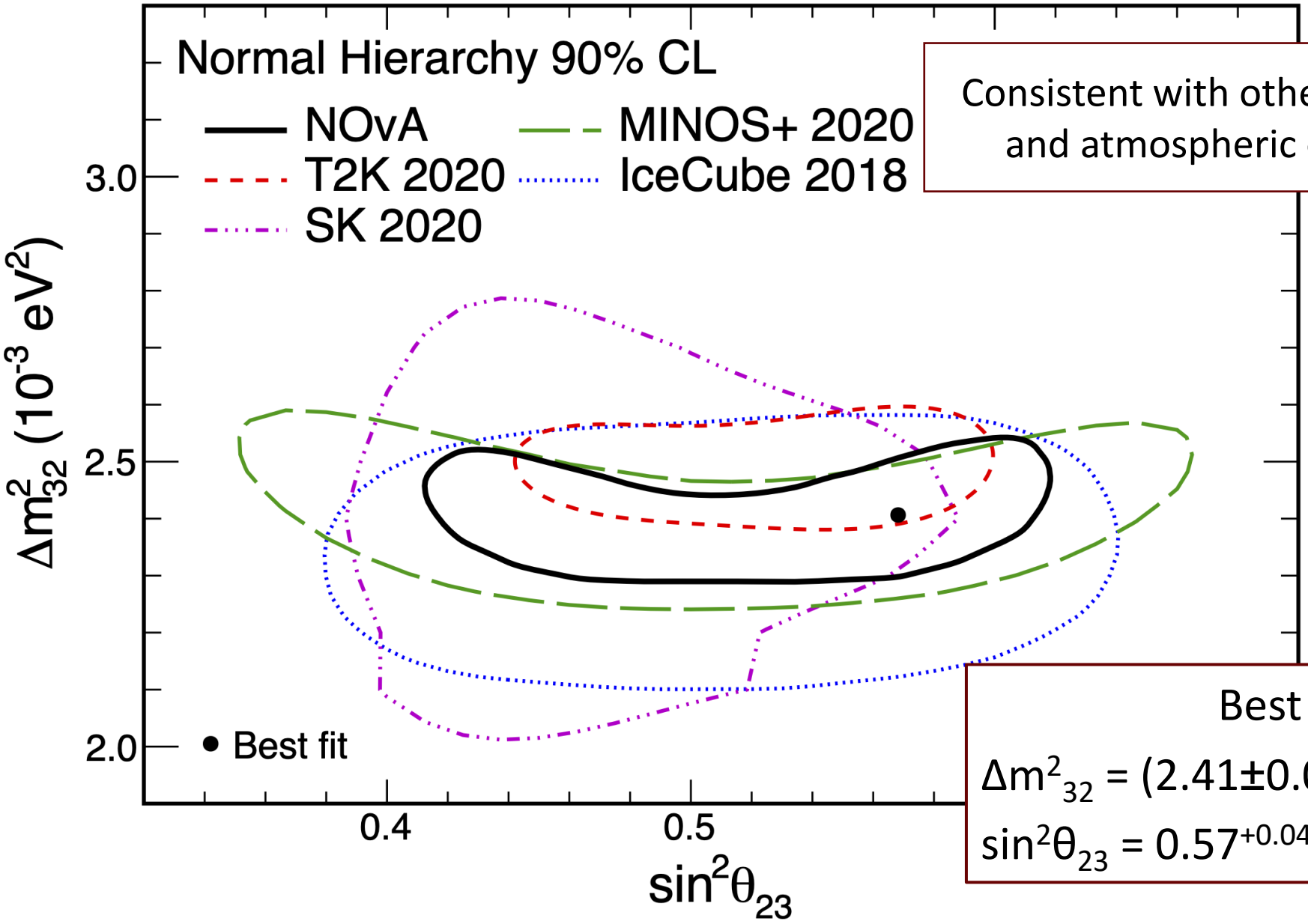
Total Observed	82
Total Prediction	85.8
Wrong-sign	1.0
Beam Bkgd.	22.7
Cosmic Bkgd.	3.1
Total Bkgd.	26.8



Total Observed	33
Total Prediction	33.2
Wrong-sign	2.3
Beam Bkgd.	10.2
Cosmic Bkgd.	1.6
Total Bkgd.	14.0

>4σ evidence of $\bar{\nu}_e$ appearance

NOvA Preliminary



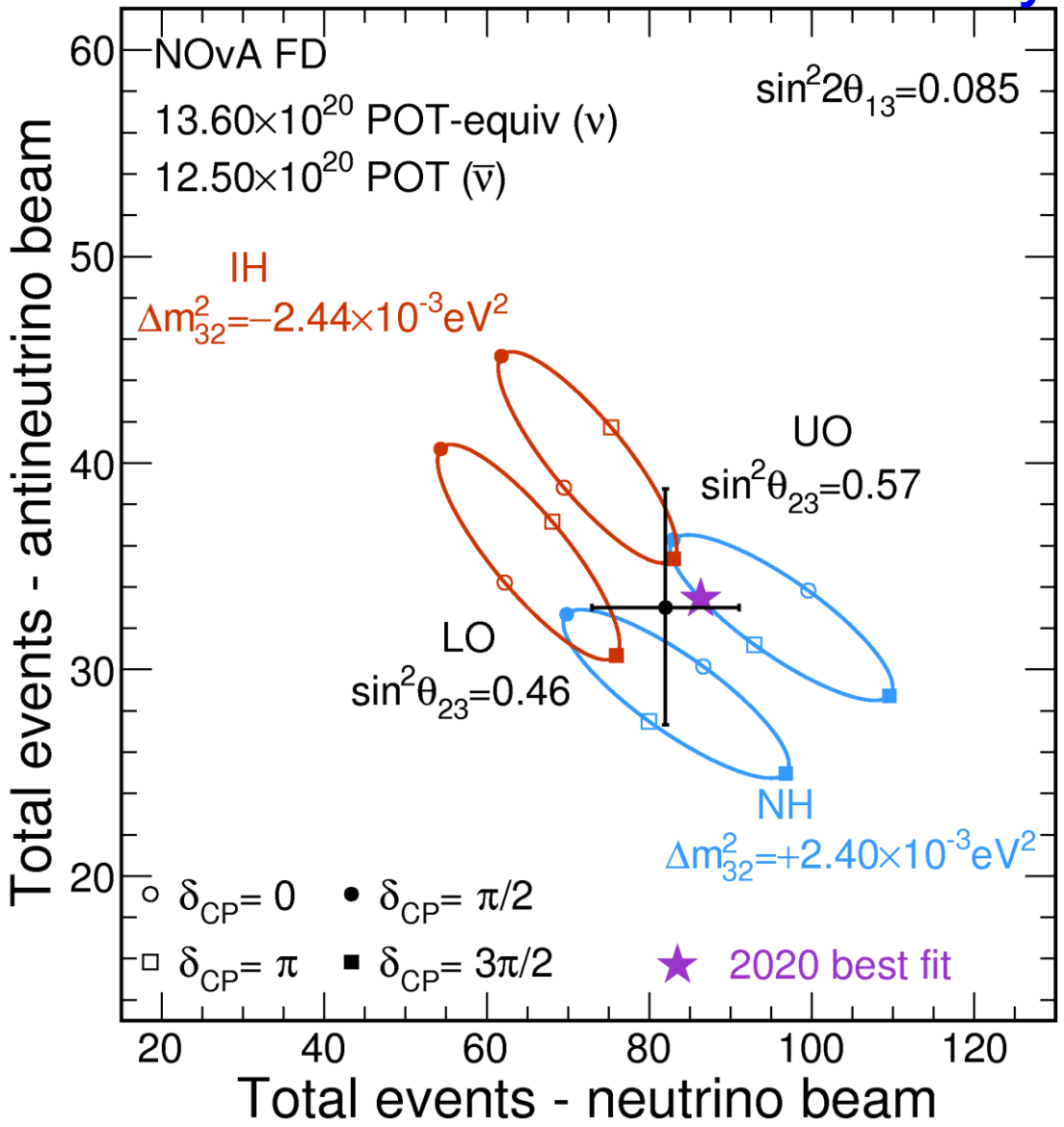
Consistent with other long-baseline and atmospheric experiments.

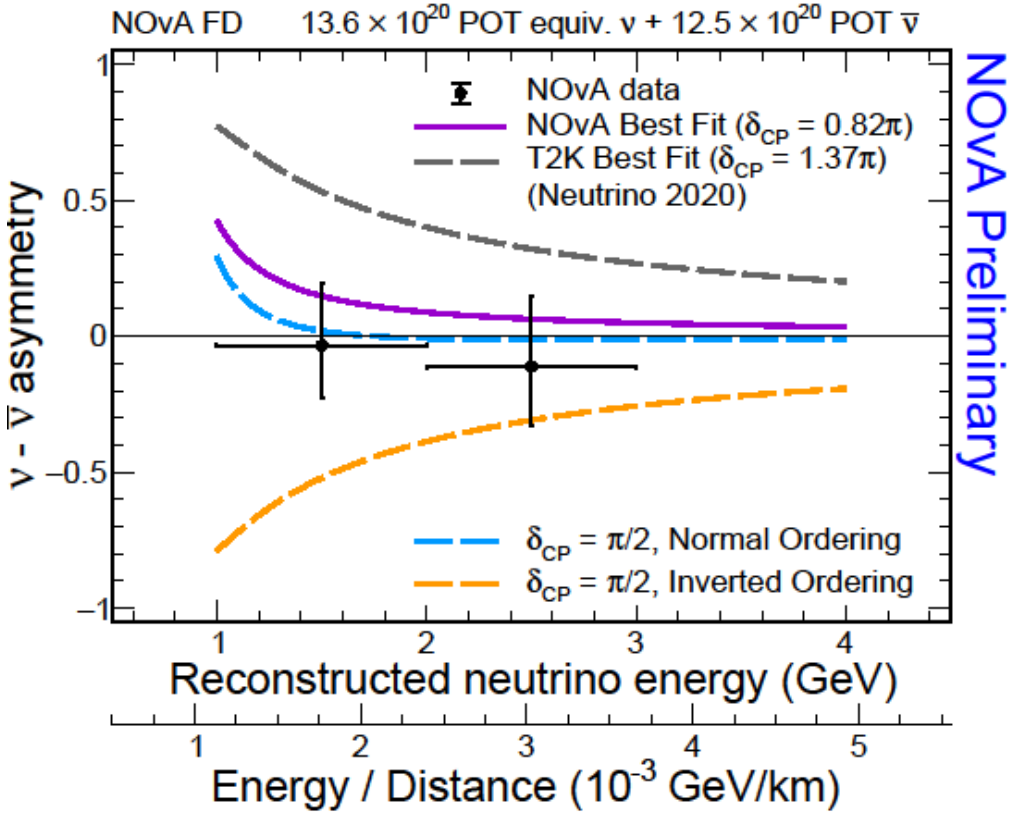
Best Fit

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

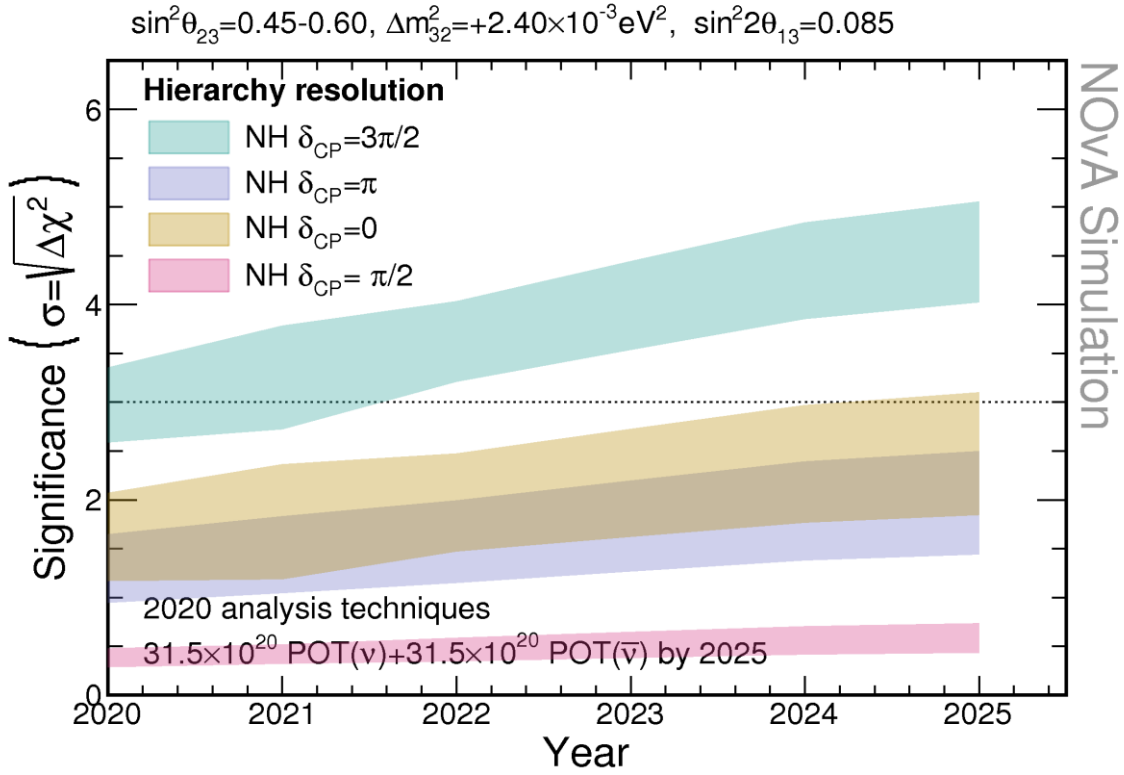
NOvA Preliminary

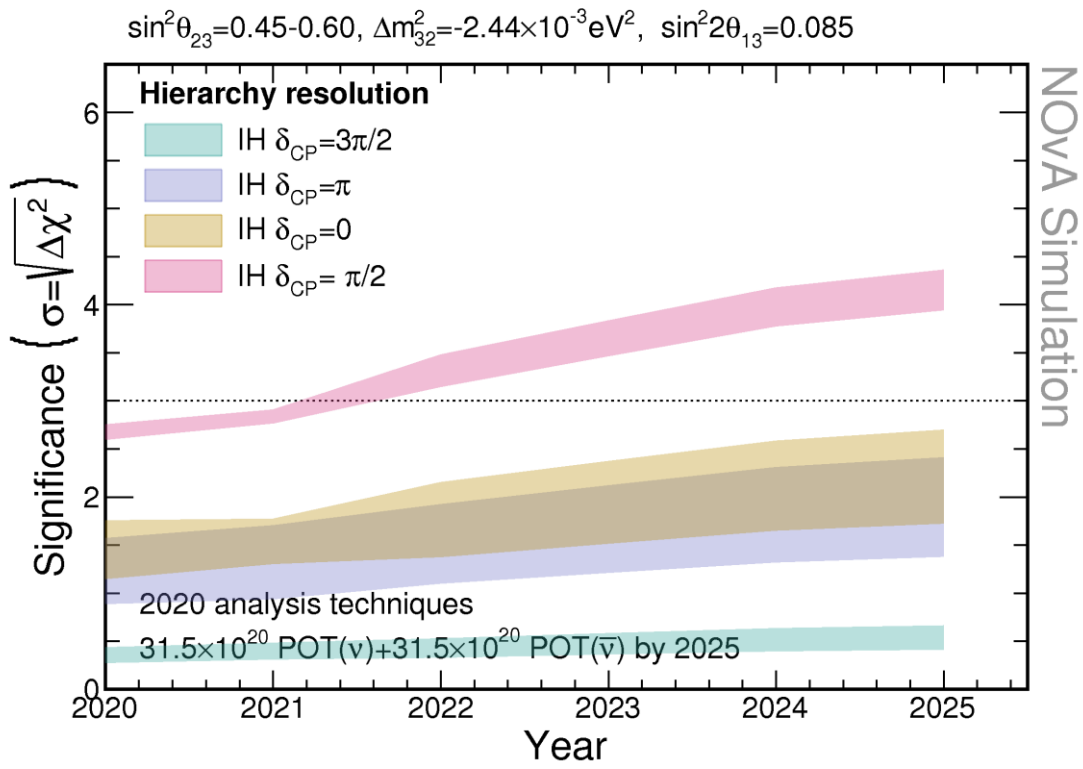




- We see no strong asymmetry in the rates of ν_e and $\bar{\nu}_e$
- Slight preference for Normal Hierarchy, Upper Octant
- Exclude IH $\delta = \pi/2$ at >3σ
- Disfavor NH $\delta = 3\pi/2$ at ~2σ

Future





- Will run through 2026 with equal neutrino/antineutrino beam
- Proposed accelerator improvements and test beam program enhance NOvA's reach
- Improvements in simulation will improve analysis robustness

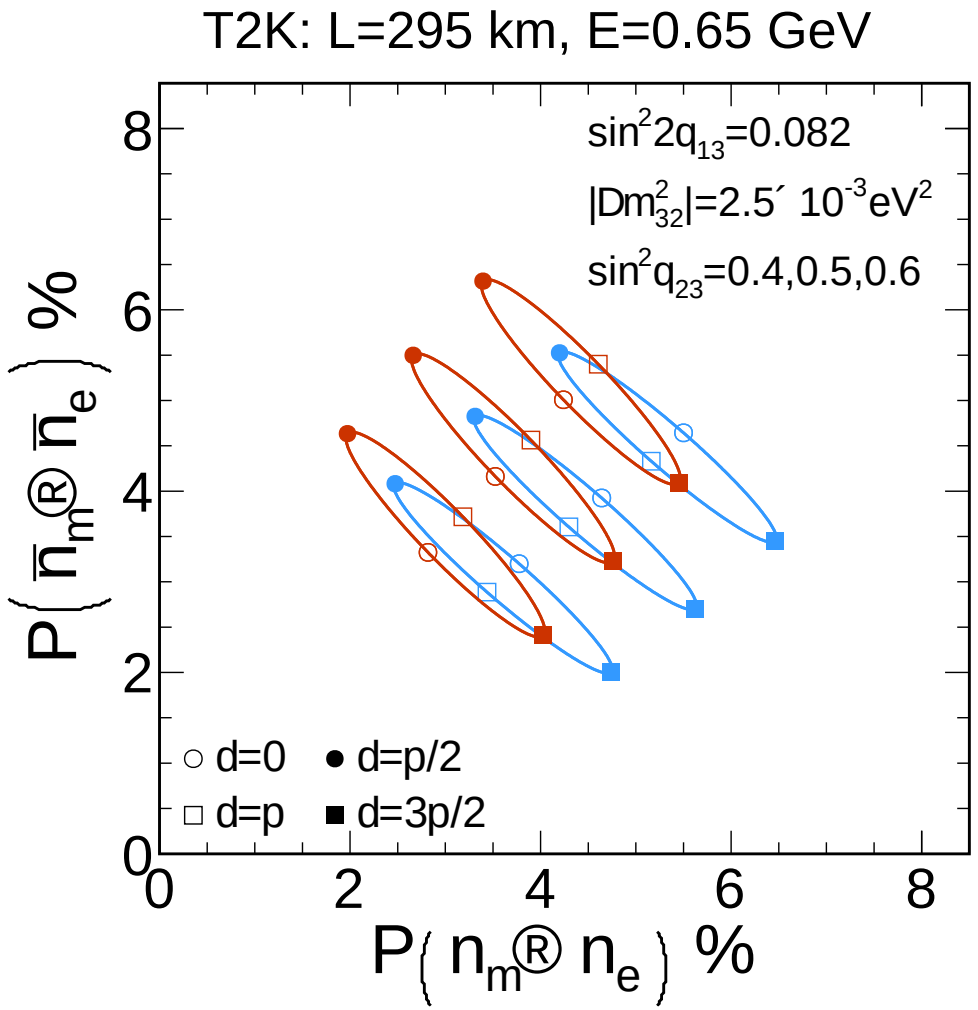
Summary

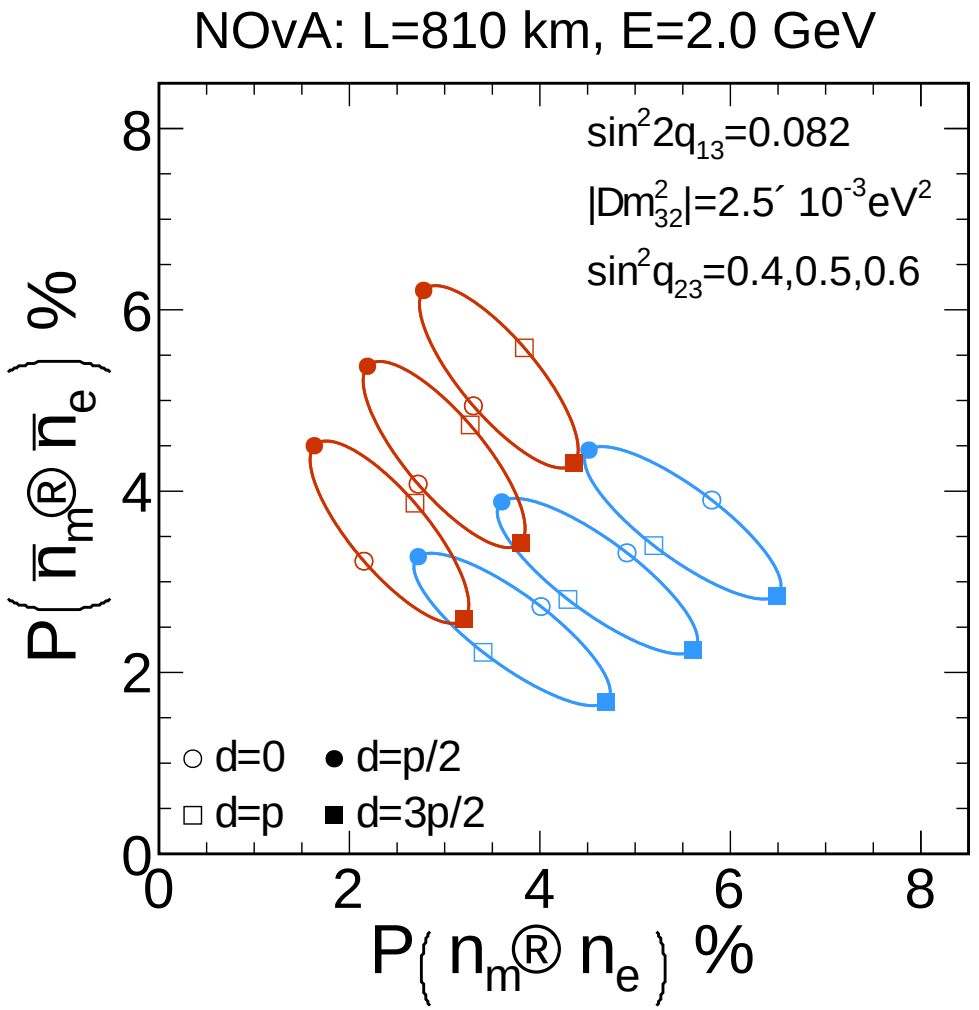
- NOvA observes >4σ evidence of electron antineutrino appearance.
- We exclude $\delta = \pi/2$ in the Inverted Hierarchy at >3σ.
- We see no strong asymmetry between rates of ν_e and $\bar{\nu}_e$.
- By 2025 we could see >3σ sensitivity to the mass hierarchy.

See our recent paper for details I couldn't cover here!

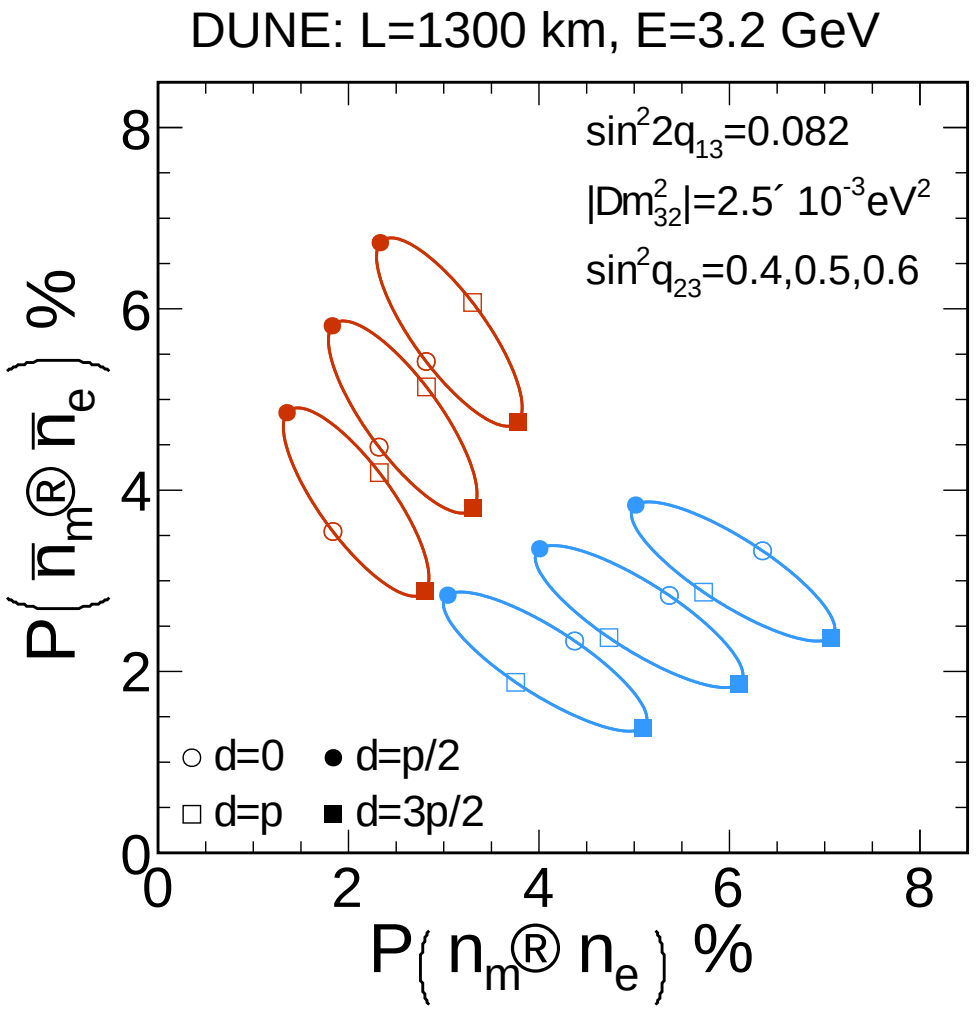
Backups

Current Long Baseline Experiments

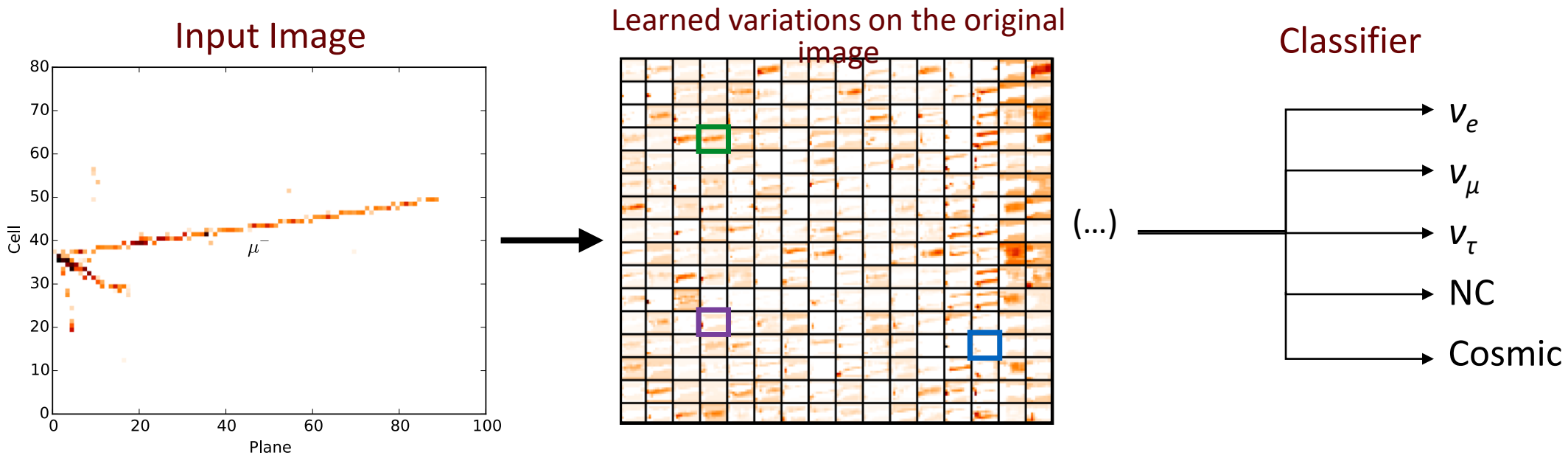




Future Long Baseline Experiments



Event Identification



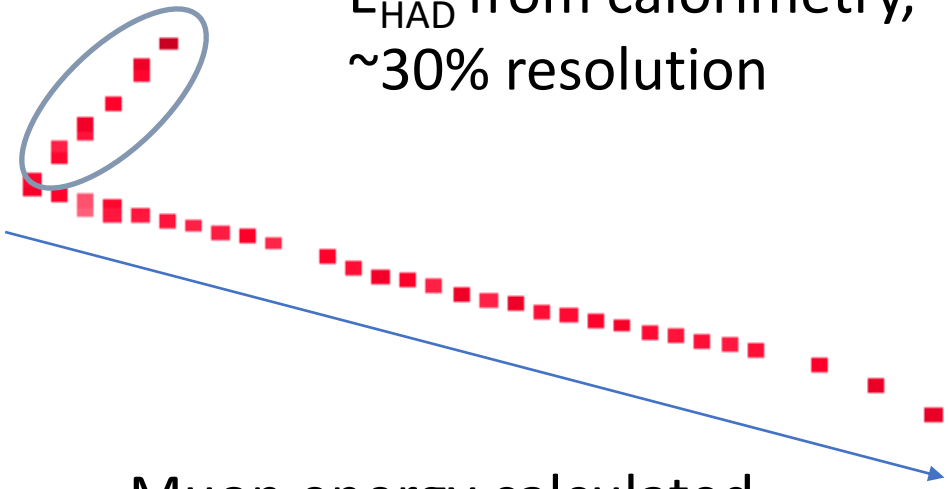
- We use a convolutional neural network (CNN) called CVN
  - Technique borrowed from computer vision community
  - Learns topological “features”
  - Mapped onto output categories

Effective exposure increase of 30% for ν_e selection (JINST 11, P09001)

Neutrino Energy

ν_μCC

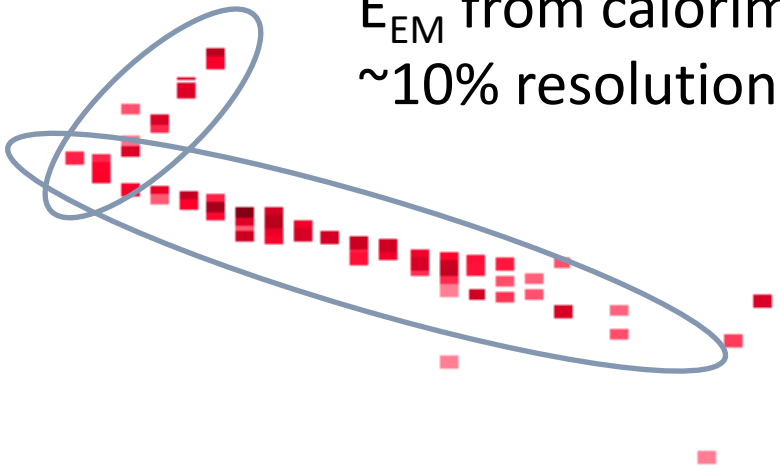
E_{HAD} from calorimetry,
~30% resolution



Muon energy calculated
by length, ~4% resolution

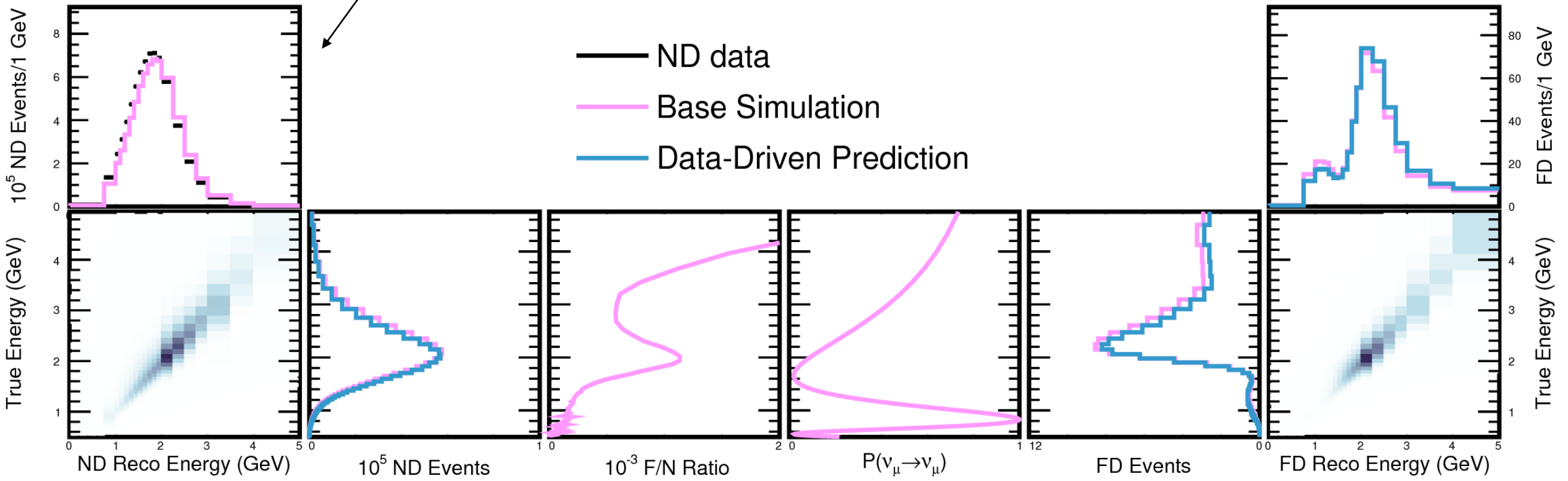
ν_eCC

E_{EM} from calorimetry,
~10% resolution

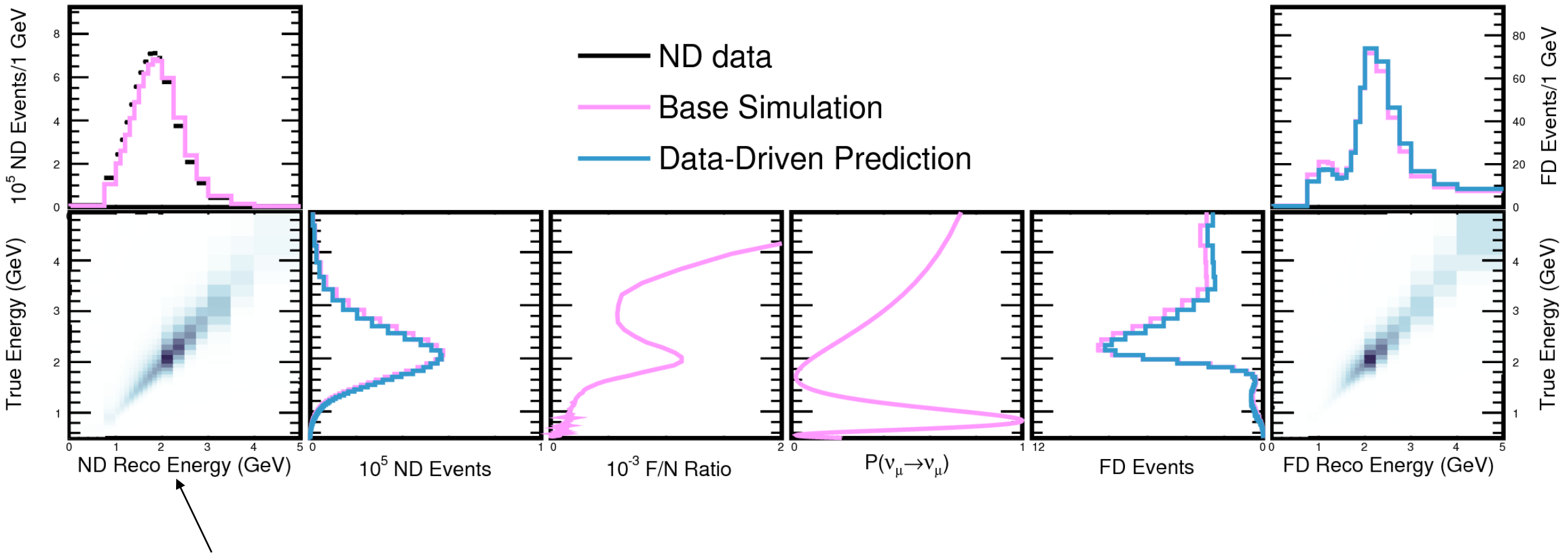


Extrapolating from Near to Far Detector

start with reconstructed ND energy spectrum

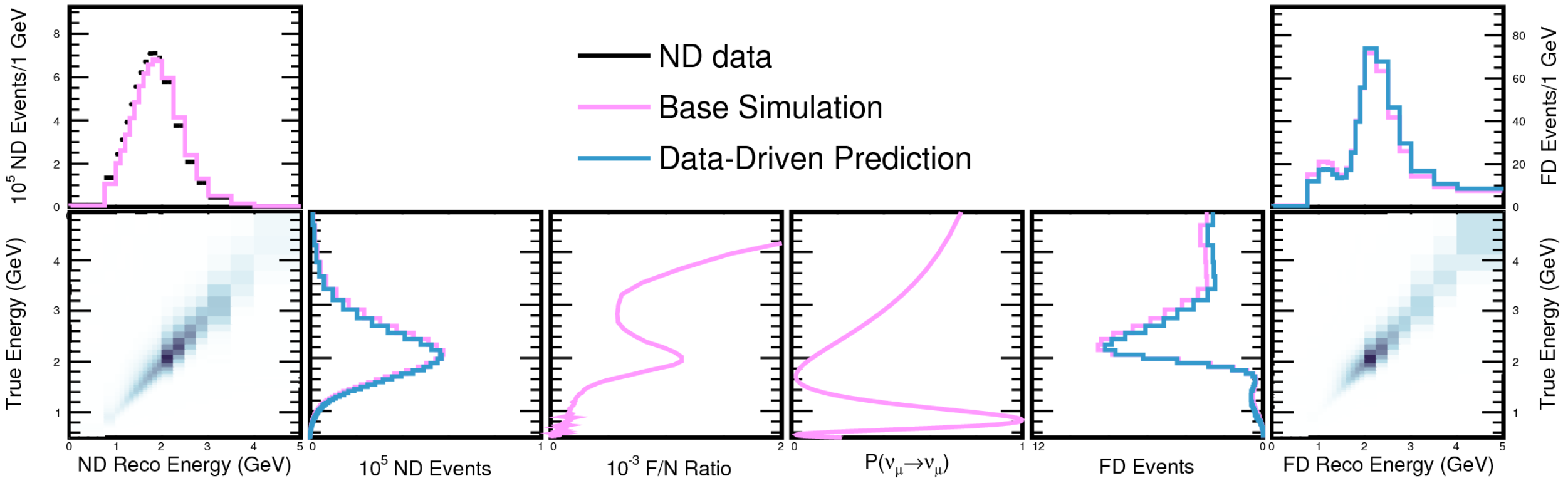


Extrapolating from Near to Far Detector



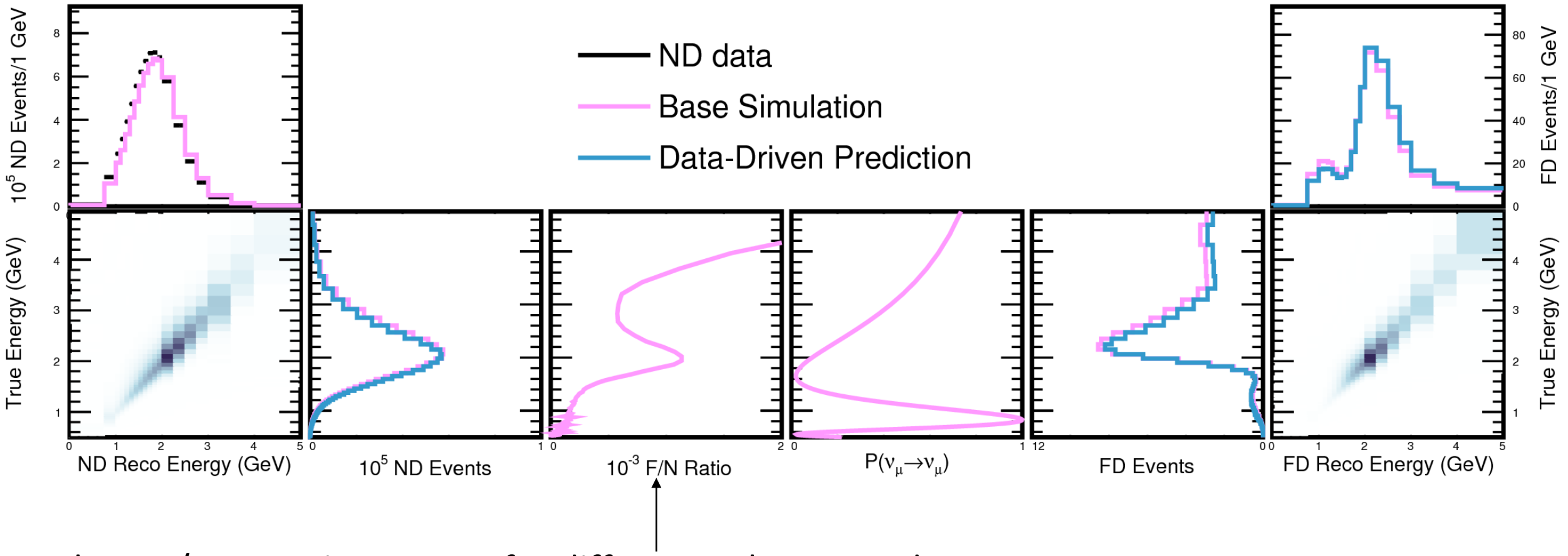
convert from reconstructed to true energy

Extrapolating from Near to Far Detector



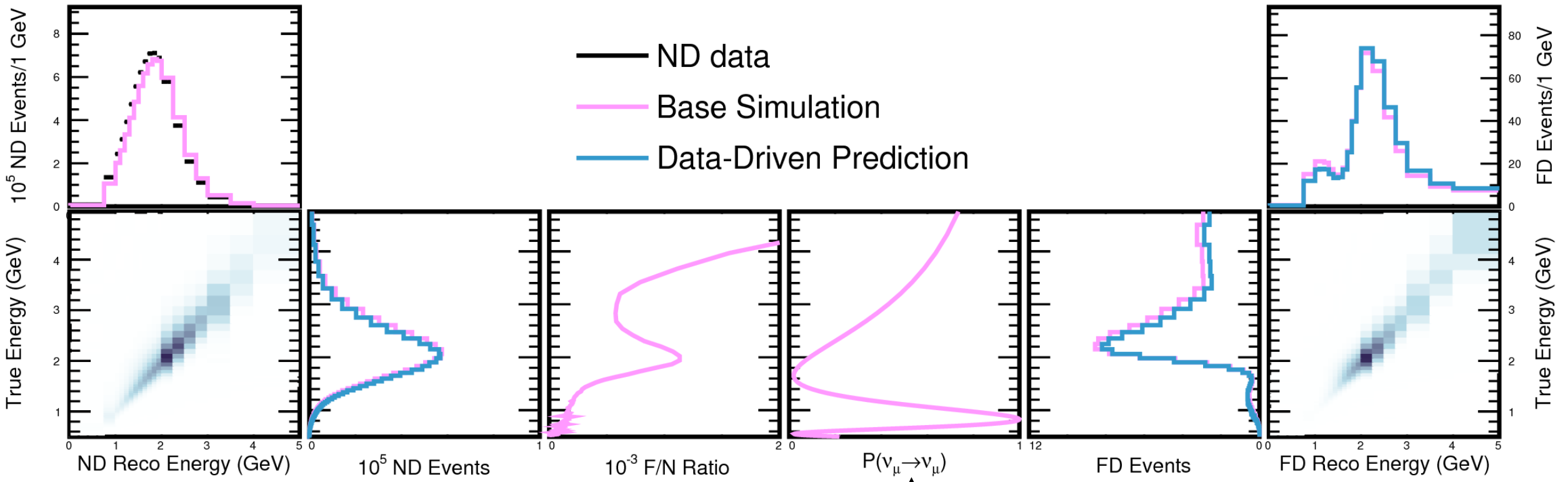
this gives you the true ND energy spectrum

Extrapolating from Near to Far Detector



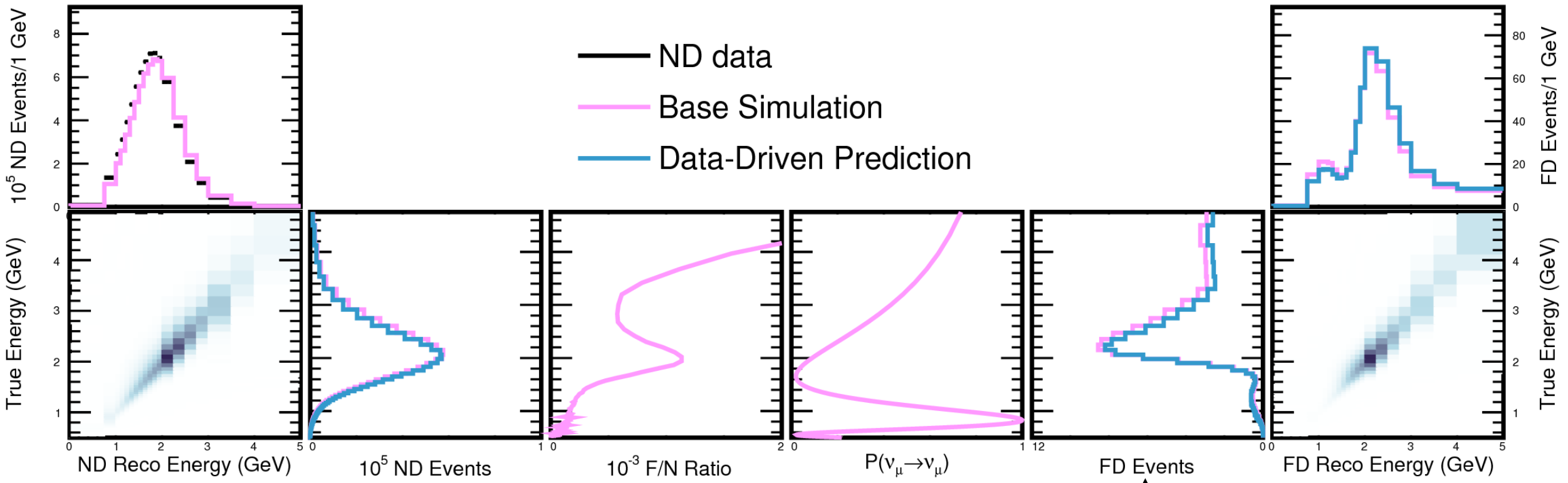
the Far/Near ratio corrects for differences between detectors e.g. geometry, acceptance

Extrapolating from Near to Far Detector



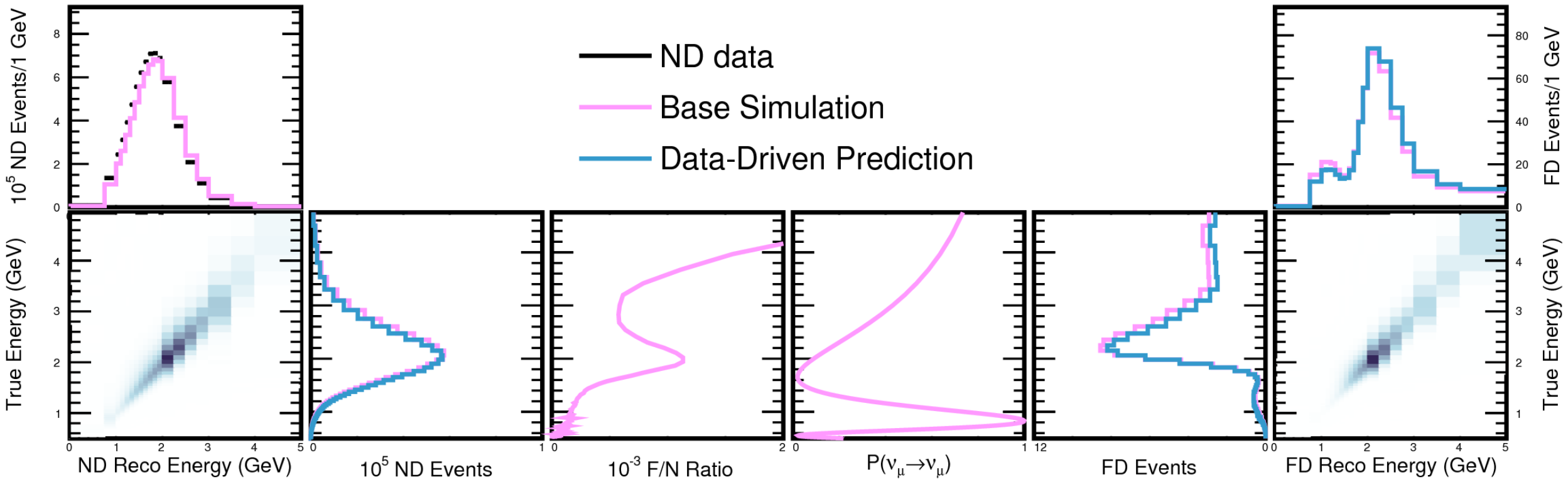
apply survival probability

Extrapolating from Near to Far Detector



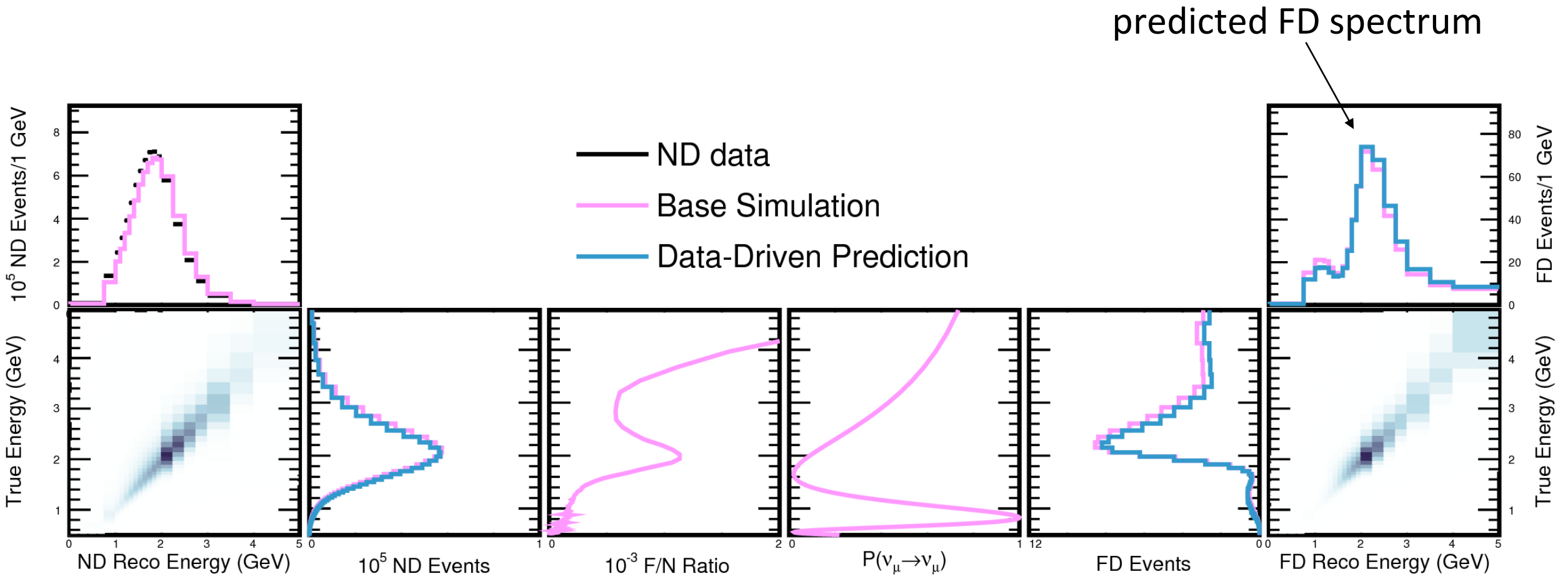
true energy spectrum at the FD

Extrapolating from Near to Far Detector

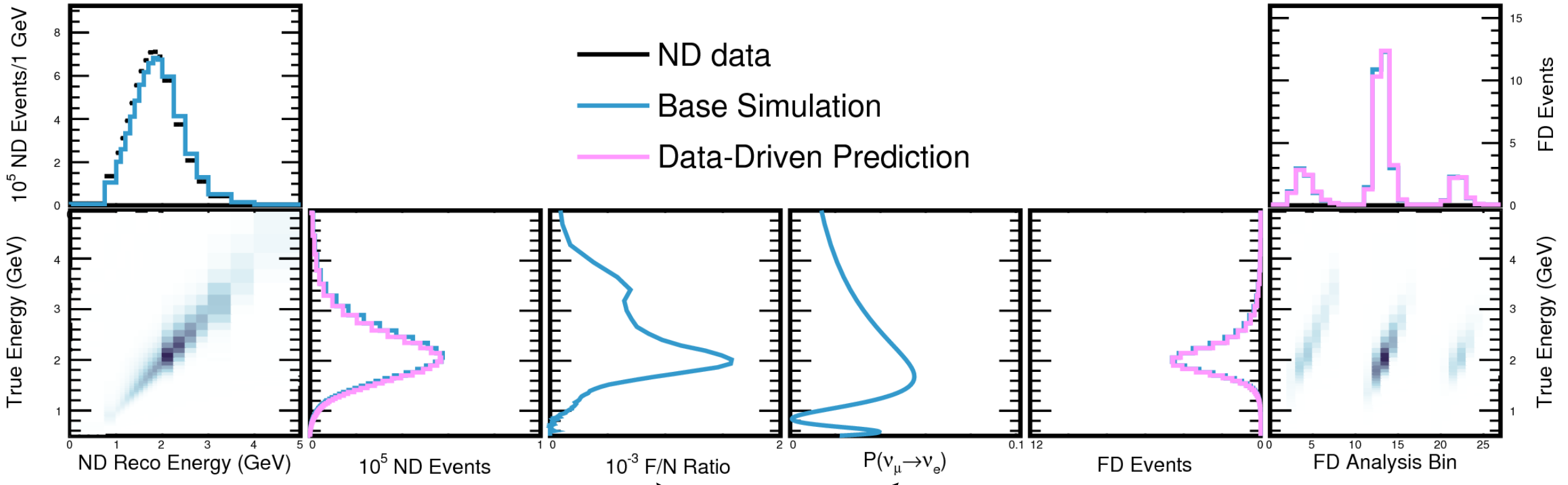


convert back to reconstructed space

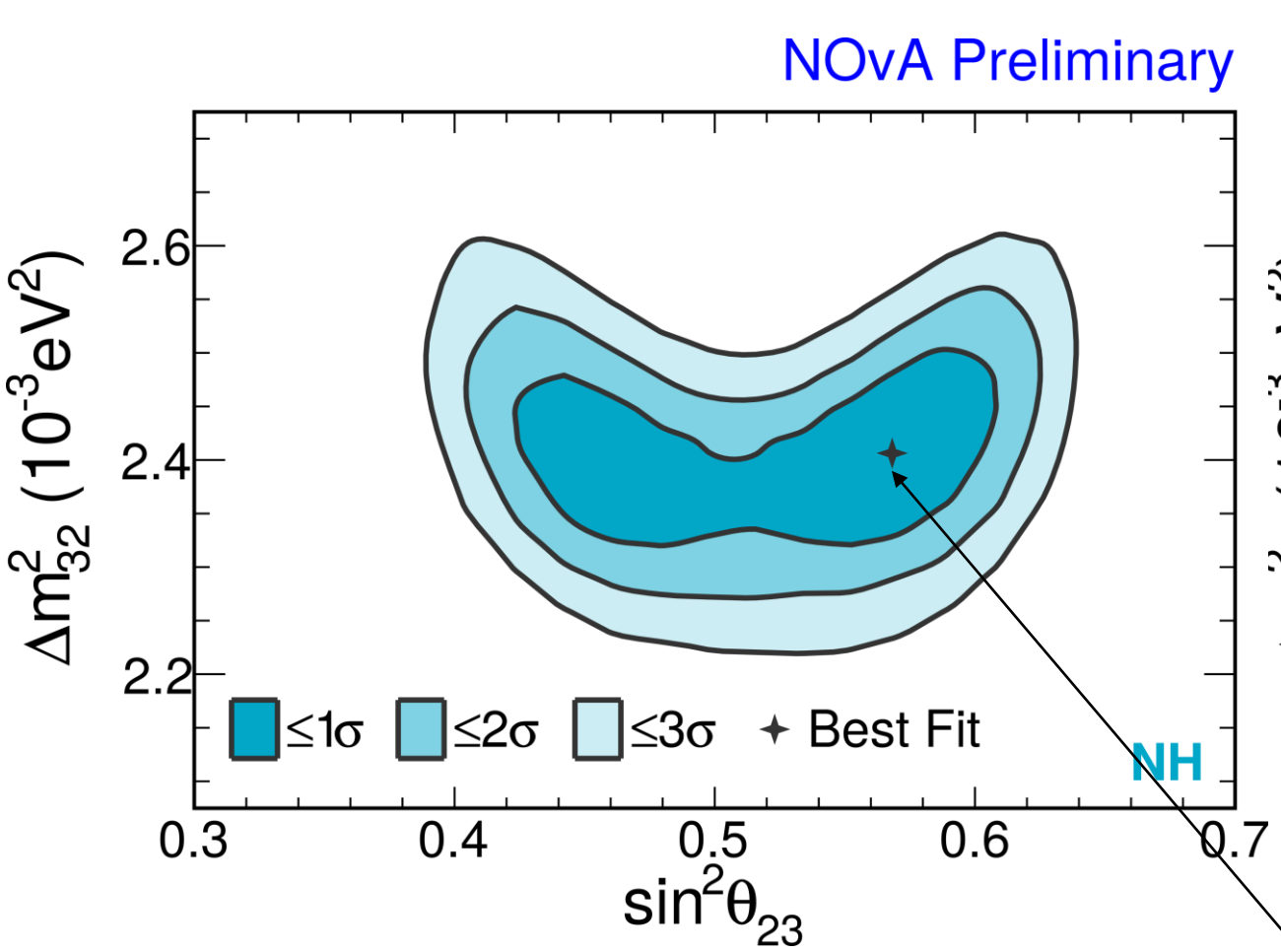
Extrapolating from Near to Far Detector

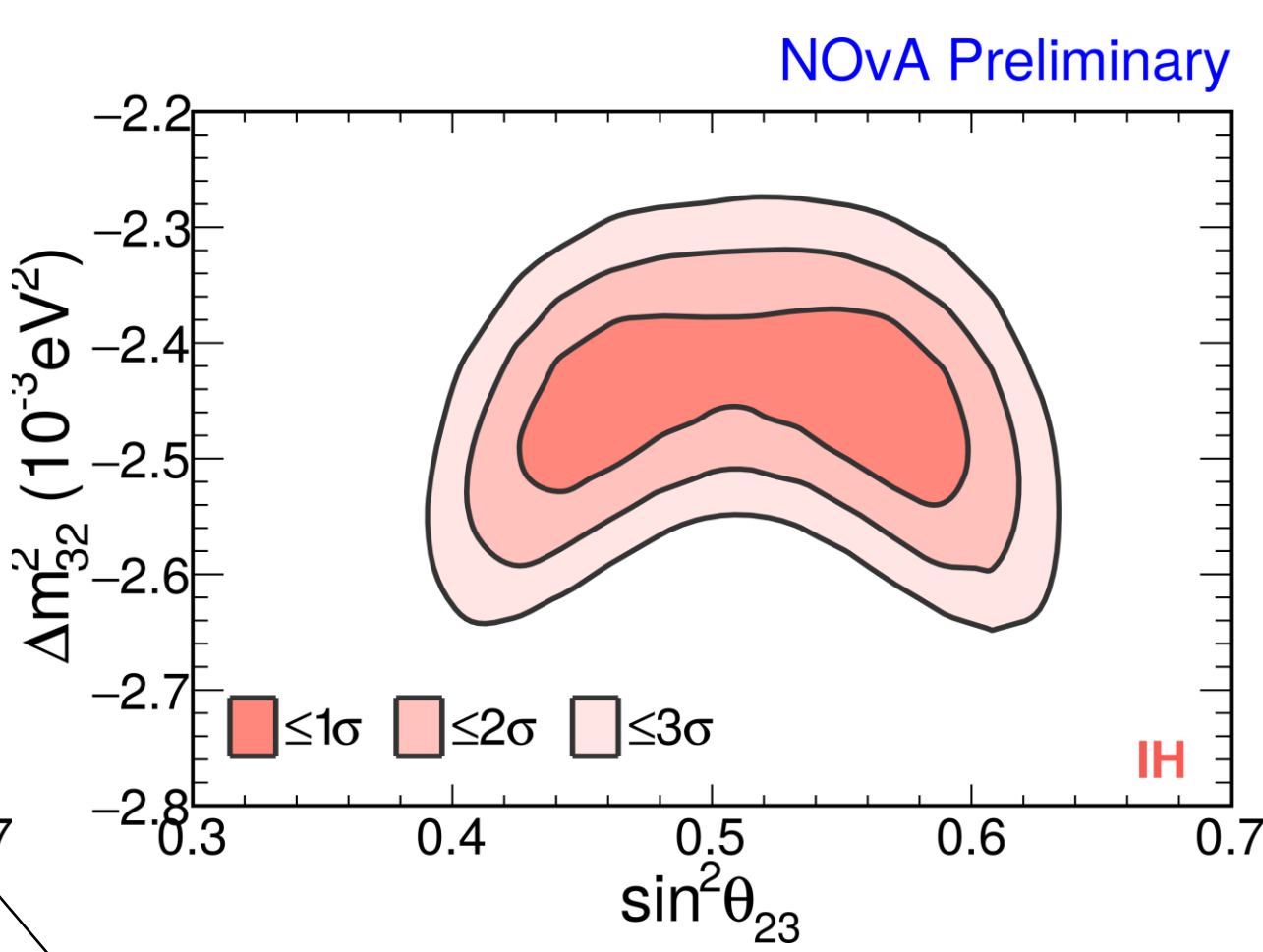


Extrapolating from Near to Far Detector



changes for ν_e: different F/N ratio, oscillation probability



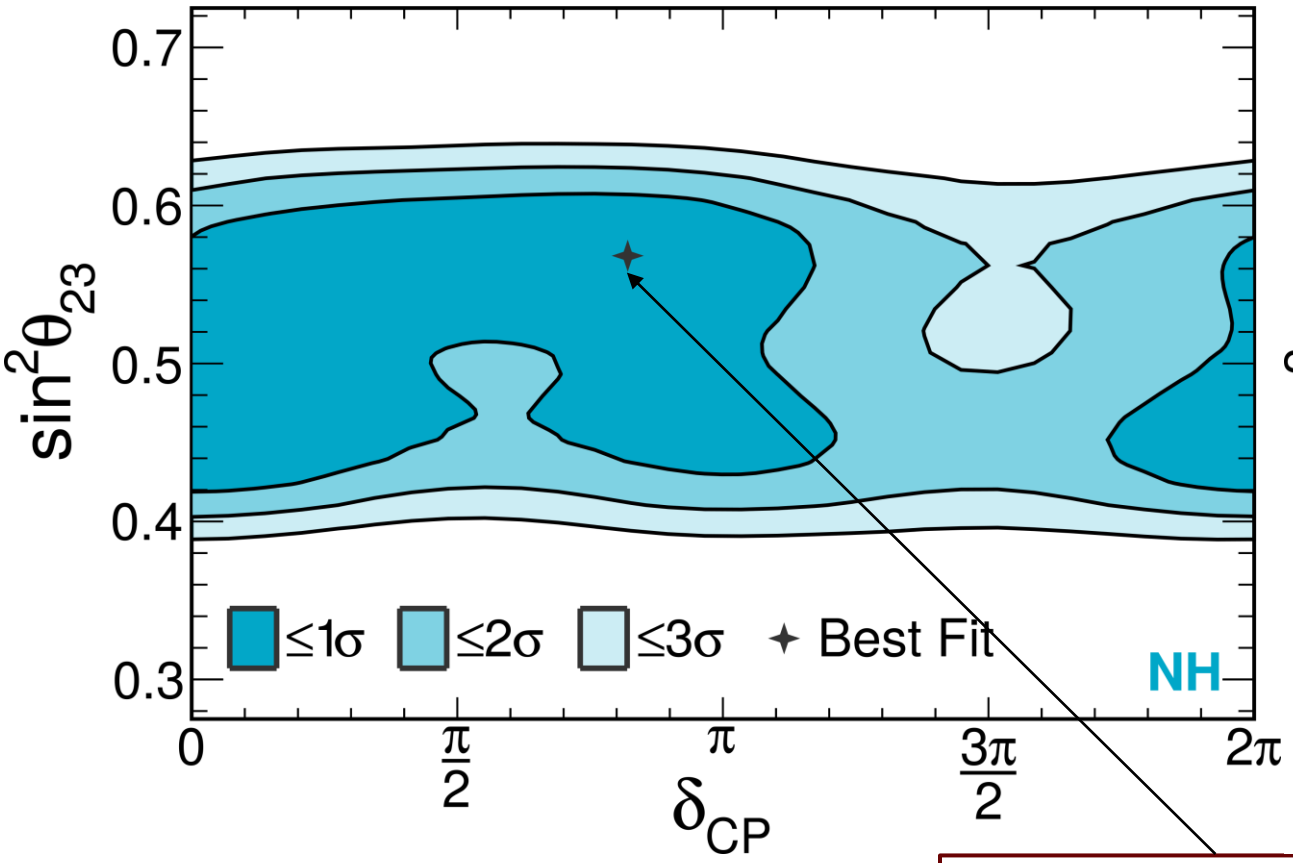


Best Fit

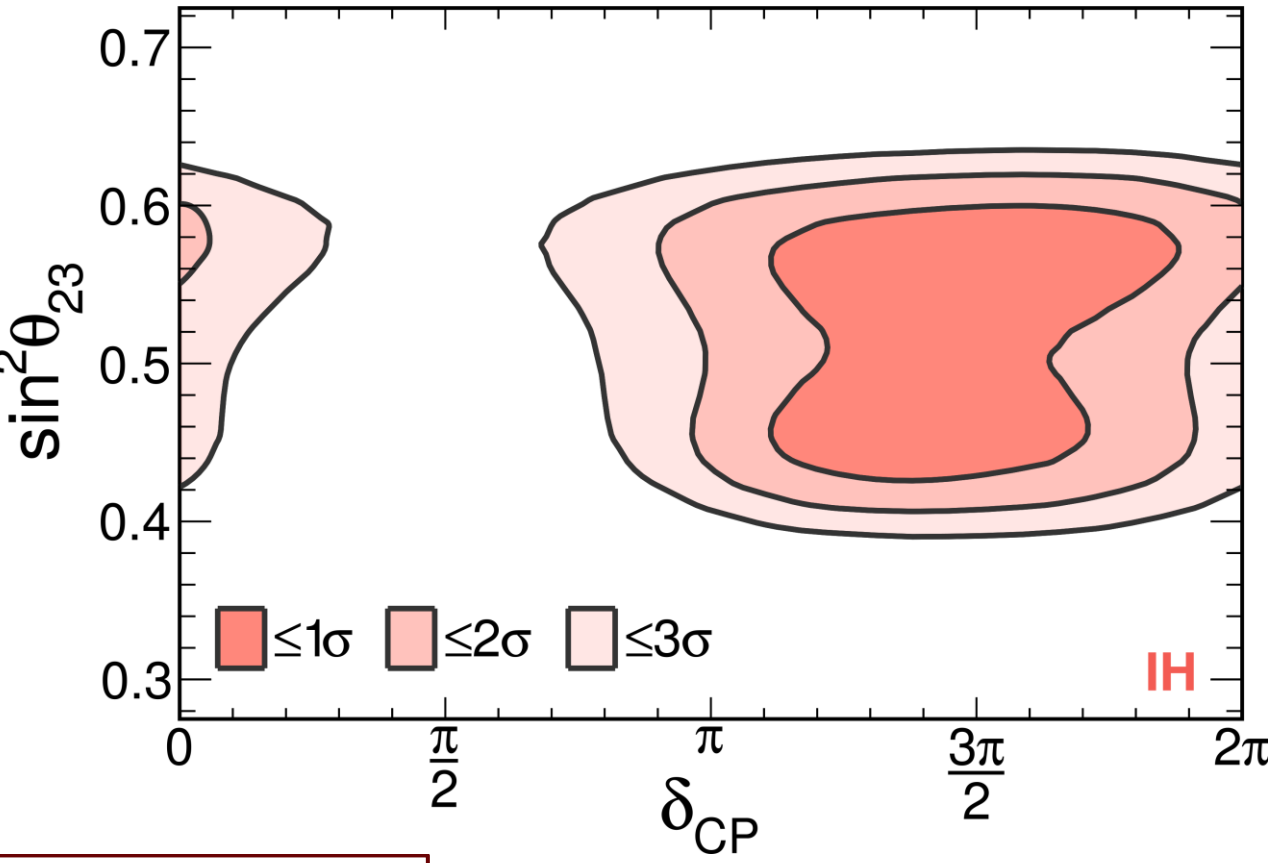
$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2

$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

NOvA Preliminary



NOvA Preliminary



Best Fit

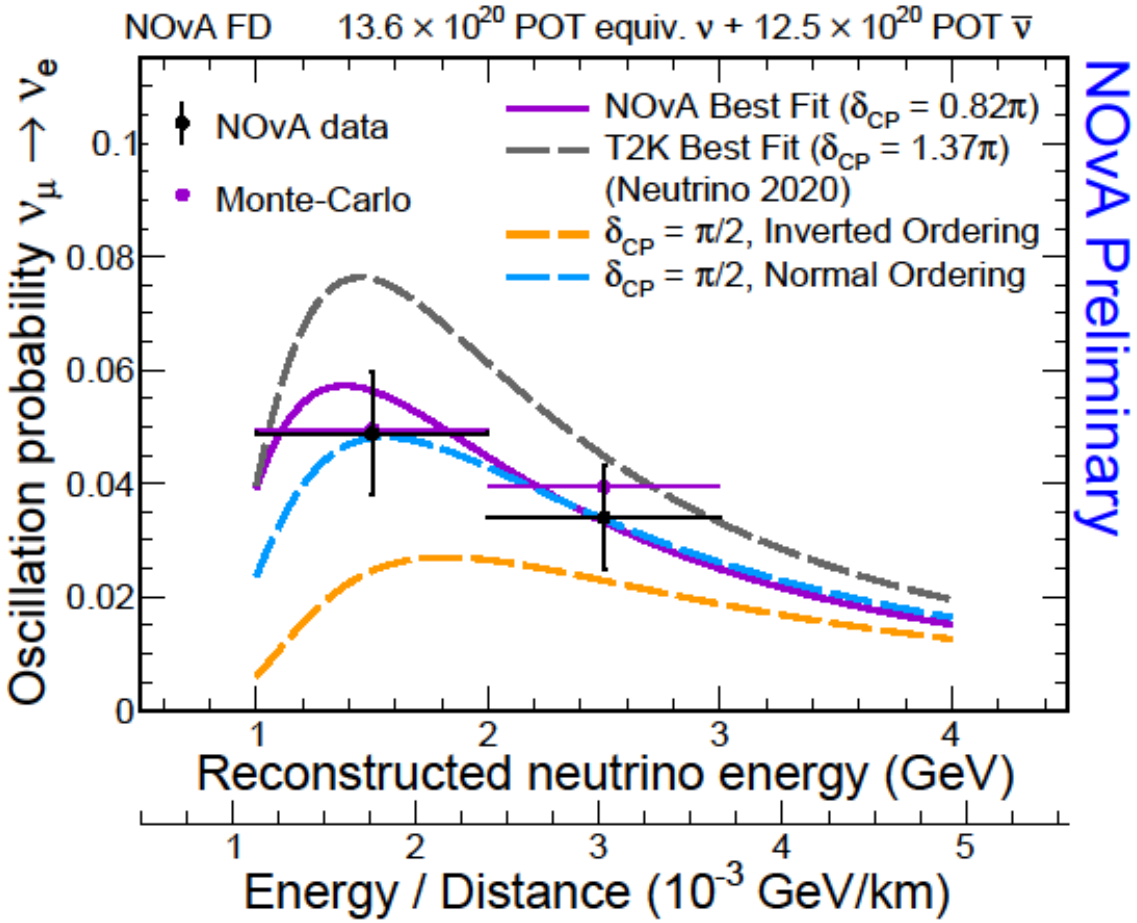
$\Delta m^2 = (2.48^{+0.11}_{-0.06}) \times 10^{-3}$ eV^2

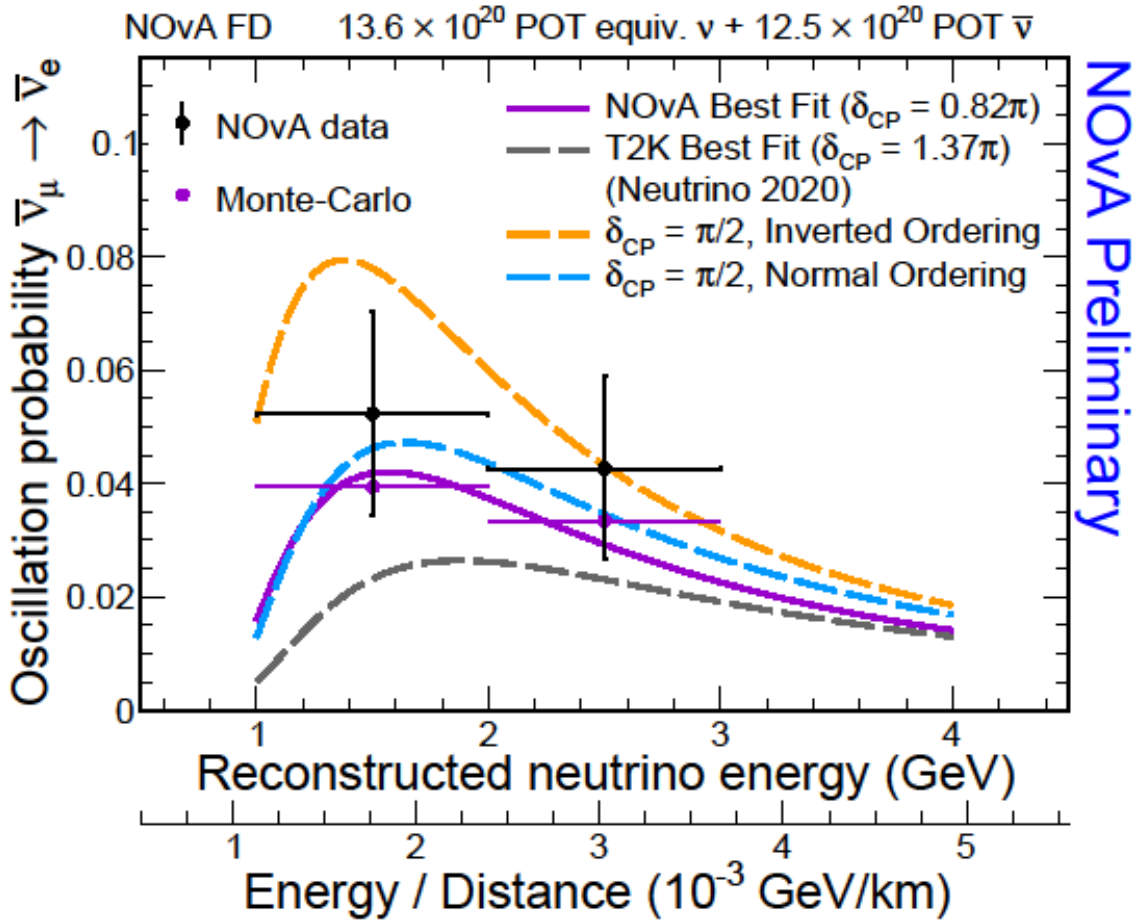
$\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$

$\delta_{CP} = 0.84\pi$

- Calibration and energy scale are two of the largest systematic uncertainties
- Will be reduced with the test beam program
- Already took some beam data, more to come after November

Asymmetry


NOvA FD 13.6 × 10^20 POT equiv. ν + 12.5 × 10^20 POT ν̄
Oscillation probability ν_μ → ν_e
NOvA data
Monte-Carlo
NOvA Best Fit (δ_CP = 0.82π)
T2K Best Fit (δ_CP = 1.37π)
(Neutrino 2020)
δ_CP = π/2, Inverted Ordering
δ_CP = π/2, Normal Ordering
NOvA Preliminary
Reconstructed neutrino energy (GeV)
Energy / Distance (10^-3 GeV/km)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Oscillation probability ν̄_μ → ν̄_e
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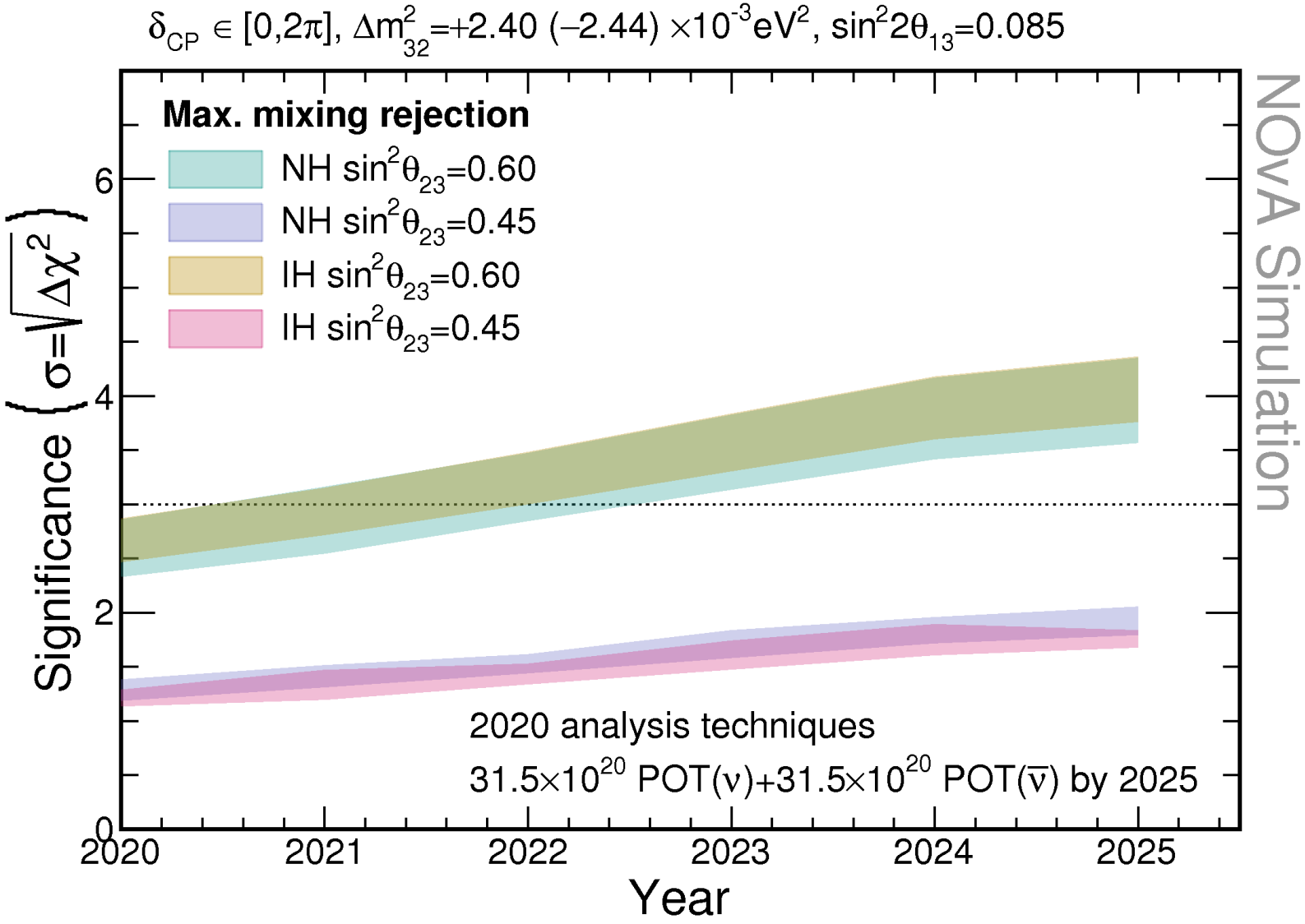
Energy / Distance (10^-3 GeV/km)

Reach – Maximal Mixing Rejection



Reach - δ_{CP}