Extraction of Neutrino Oscillation Parameters using Neutrino and Anti-neutrino Data with the NOvA Experiment

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On behalf of the NOvA Collaboration

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Outline

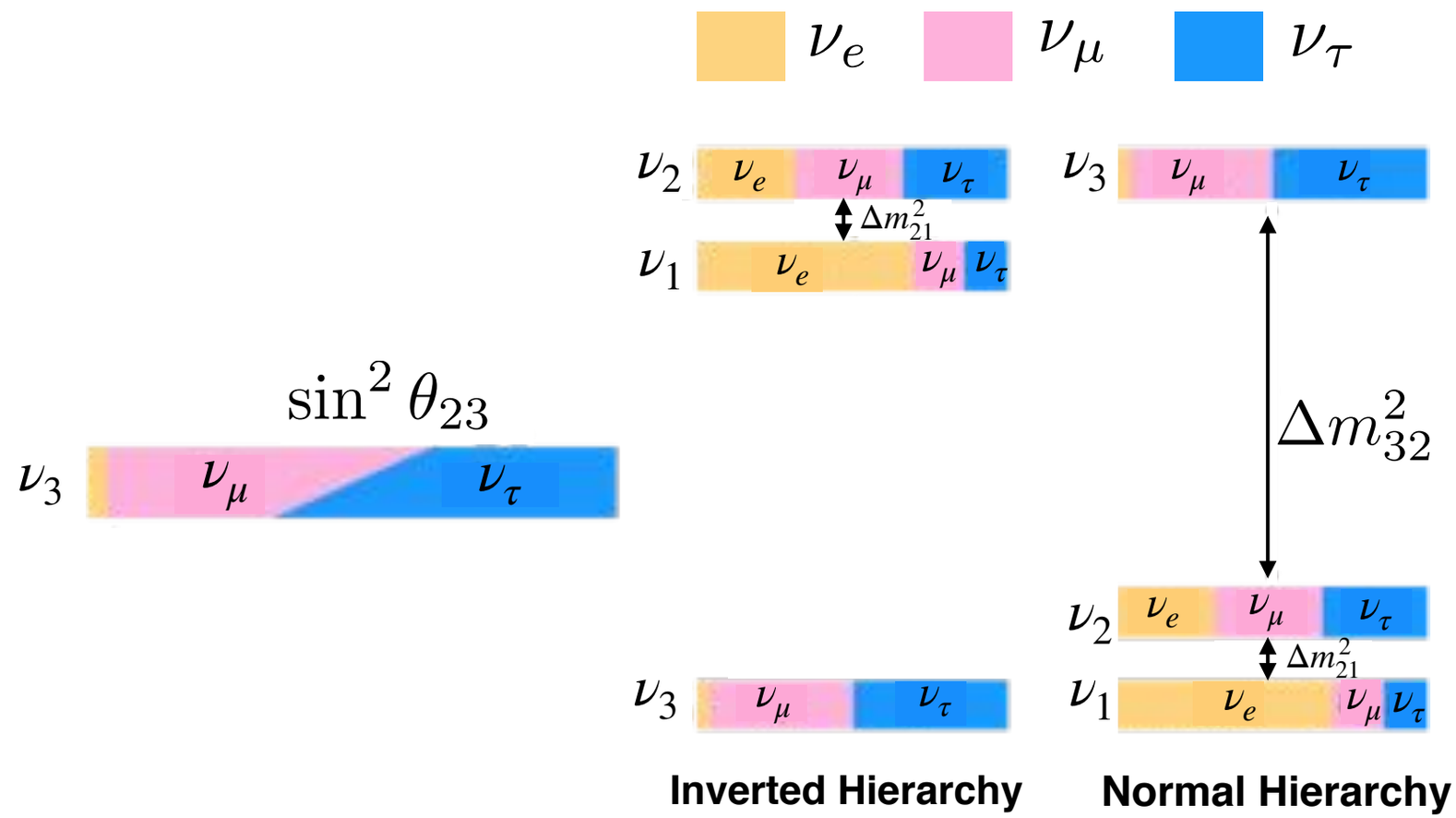
- Basic, important and unanswered questions in the neutrino sector
- Introduction to the NOvA experiment and detectors
- Production of neutrino beam at Fermilab
- ν_μ disappearance and ν_e appearance data and predictions
- Results of the simultaneous fit to the disappearance and appearance data
- Summary

Unanswered Questions in the Neutrino Sector

- **Mass hierarchy:** Do neutrino masses follow normal or inverted mass hierarchy?

- **CP violation (δ_{cp}):** Are neutrinos different from anti-neutrinos?

- **θ_{23} angle:** Does ν_μ and ν_τ mixes maximally?



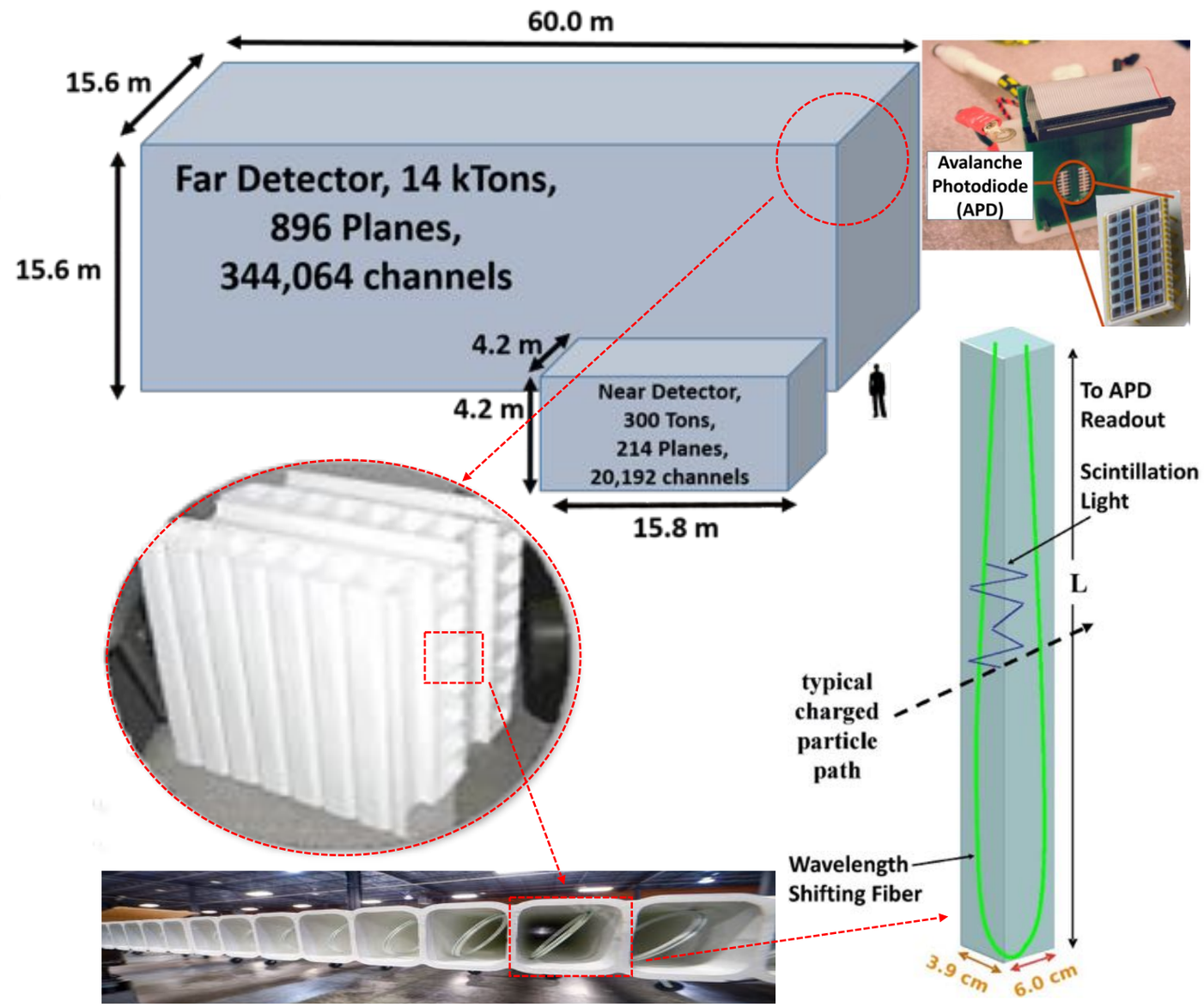
The NOvA Experiment

- **NOvA** (**N**uMI **O**ff-Axis **ν_e A**ppearance) is a two detector, long-baseline, neutrino oscillation experiment
  - **NuMI** (**Neu**trinos at **M**ain **I**njector) is 95% ν_μ in neutrino mode and 93% $\bar{\nu}_\mu$ in anti-neutrino mode
  - NOvA is 14.6 mrad off-axis from the NuMI beam, observed energy spectrum peaks at 2 GeV peak
  - The Near detector (ND) is onsite at Fermilab, 1 km from neutrino source
  - The Far detector (FD) at Ash River, MN, 810 km from the target

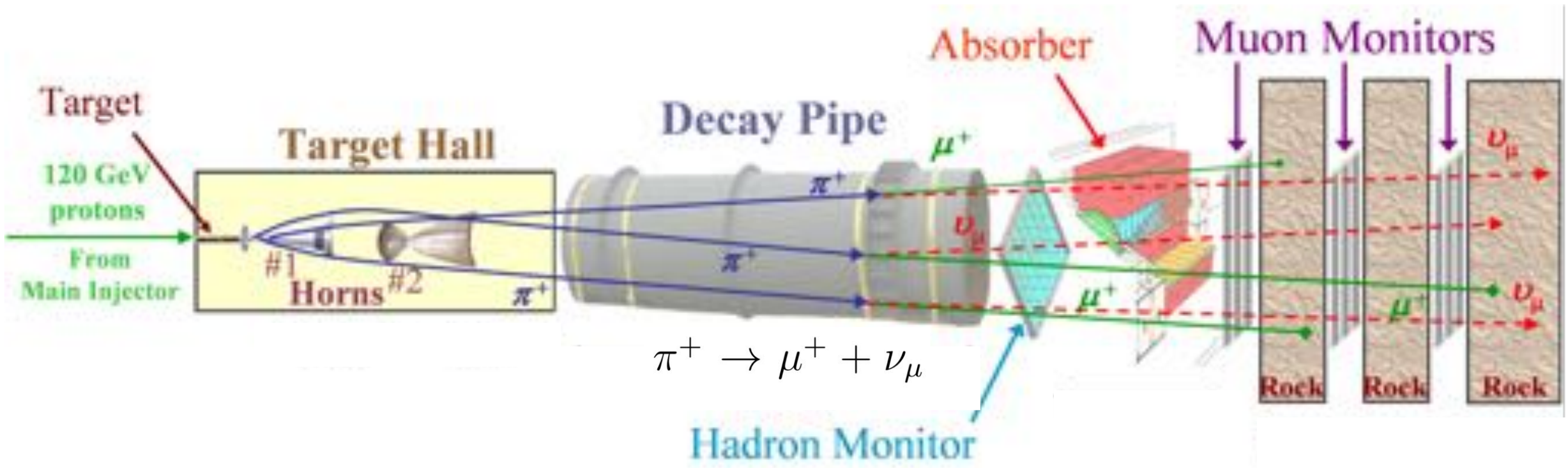
- **Oscillation channels**:
  - $\nu_\mu \rightarrow \nu_\mu$ disappearance
  - $\nu_\mu \rightarrow \nu_e$ appearance
  - Anti-neutrino modes

NOvA Detectors

- NOvA far and near detectors are functionally identical
  - Liquid scintillator detectors and made up of polyvinyl chloride (PVC)
  - Alternating horizontal and vertical planes are used to make 3D tracks of the charged particles
- The neutrino beam is measured by the ND before oscillations and by the FD after oscillations
- The functionally identical ND is also used to make predictions of signal and background components in the FD



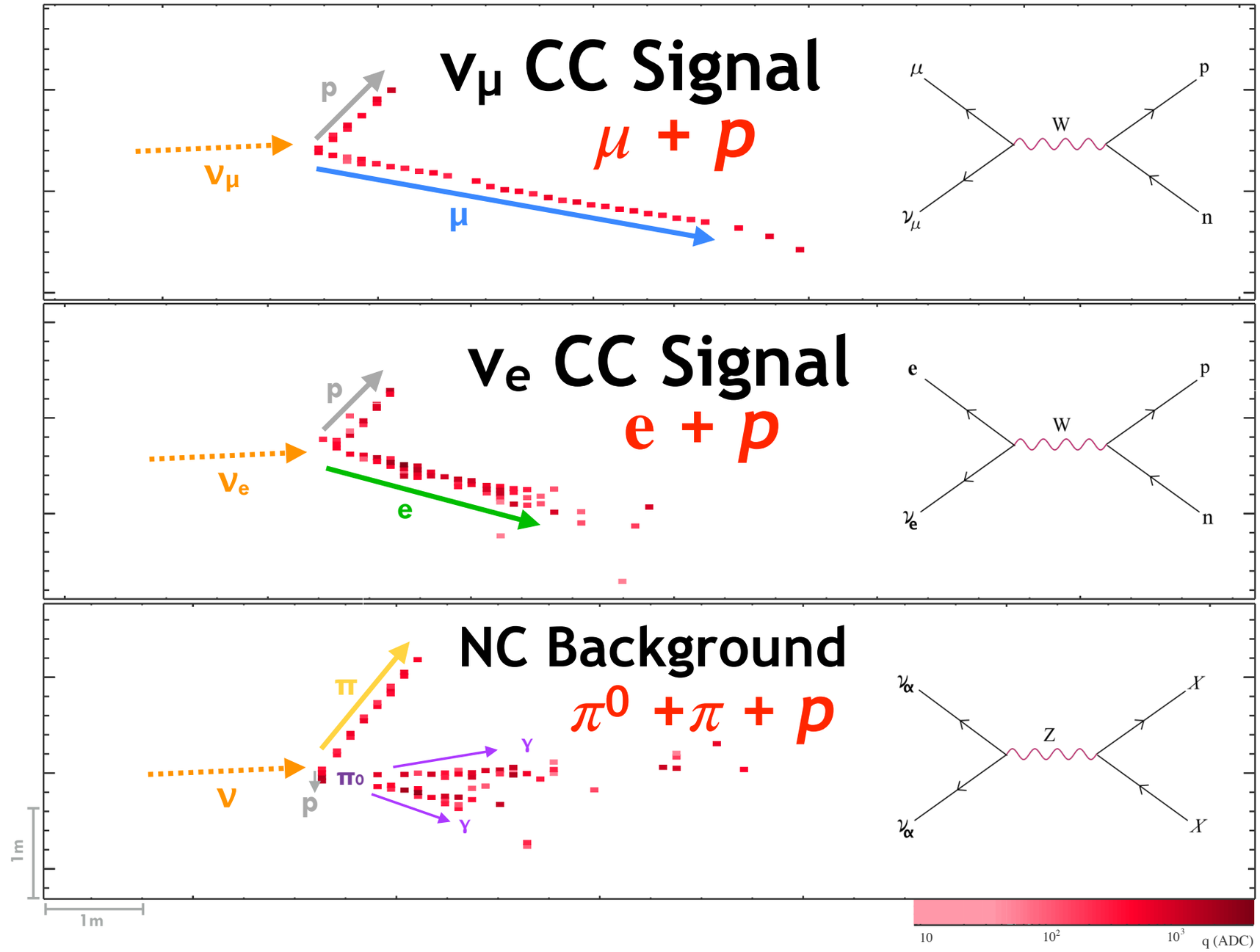
NuMI (Neutrinos at the Main Injector) Neutrino Beam



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- A beam of high energy protons from the Main Injector impinge on a fixed graphite target producing pions and kaons
- Magnetic horns select particles of the desired charge & momentum and focus them into a narrow beam
- Charged pions and kaons decay into muons and neutrinos in the decay pipe
- Rock after absorber filters out muon neutrinos
- Finally we are left with a beam of muon neutrinos

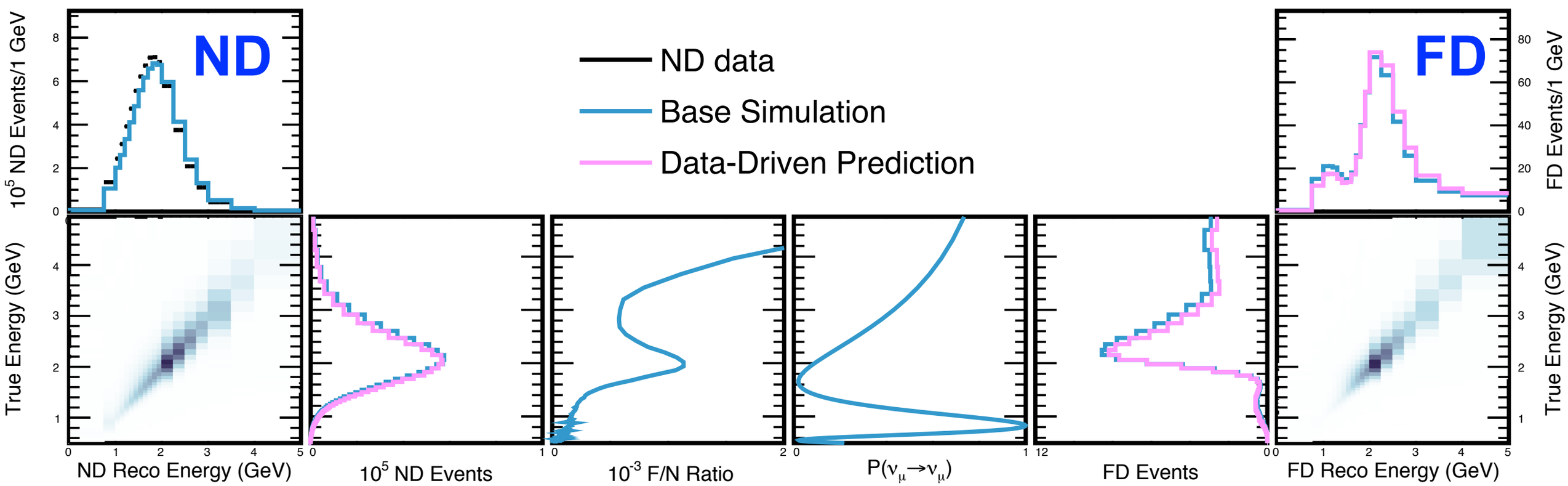
Event Topologies in NOvA



- ν_μ CC is the signal for the ν_μ ($\bar{\nu}_\mu$) disappearance analysis
- ν_e CC is the signal for the ν_e ($\bar{\nu}_e$) appearance analysis
- NC is the background in above analyses

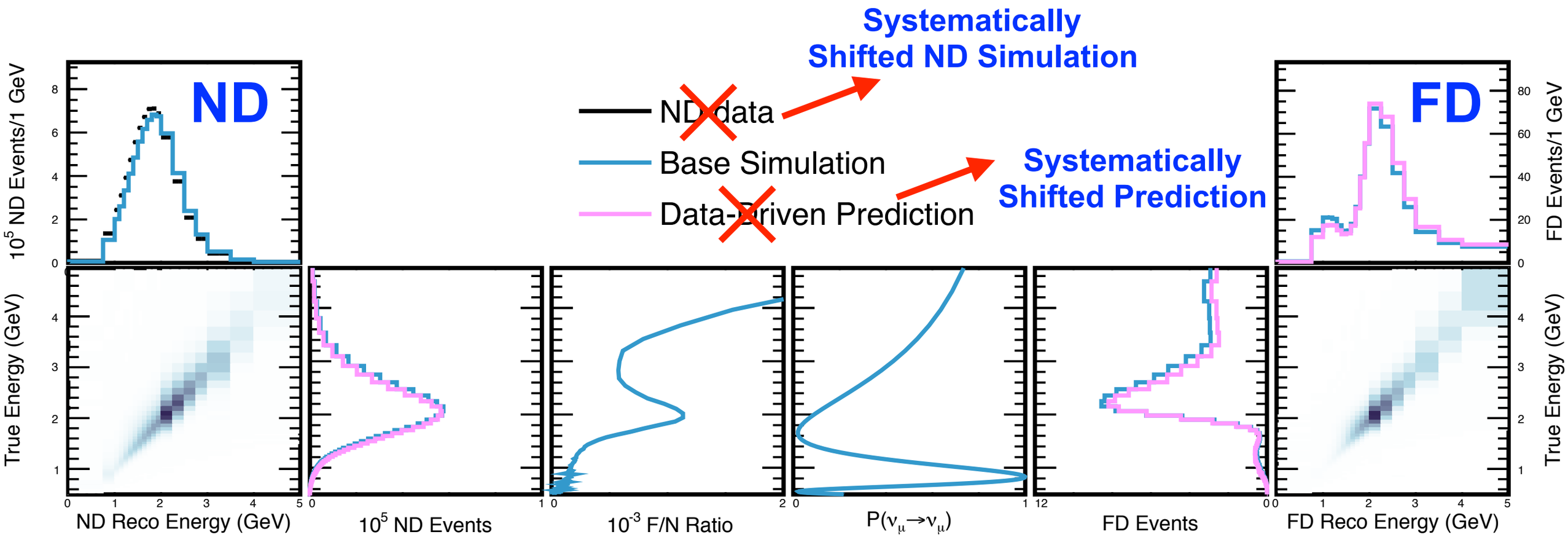
Extrapolation - FD Signal Prediction

- To make signal prediction in the FD, we start by measuring the neutrino spectrum in the ND and convert it to true energy distribution
- The measured spectrum in the ND is combined with the ratio of Far over Near (F/N) simulations and the oscillation probabilities for disappearance or appearance signal
- The extrapolated distribution in the true energy is converted to the reconstructed energy by using $E_{True} \longrightarrow E_{Reco}$ 2D energy matrix resulting into signal prediction in the FD



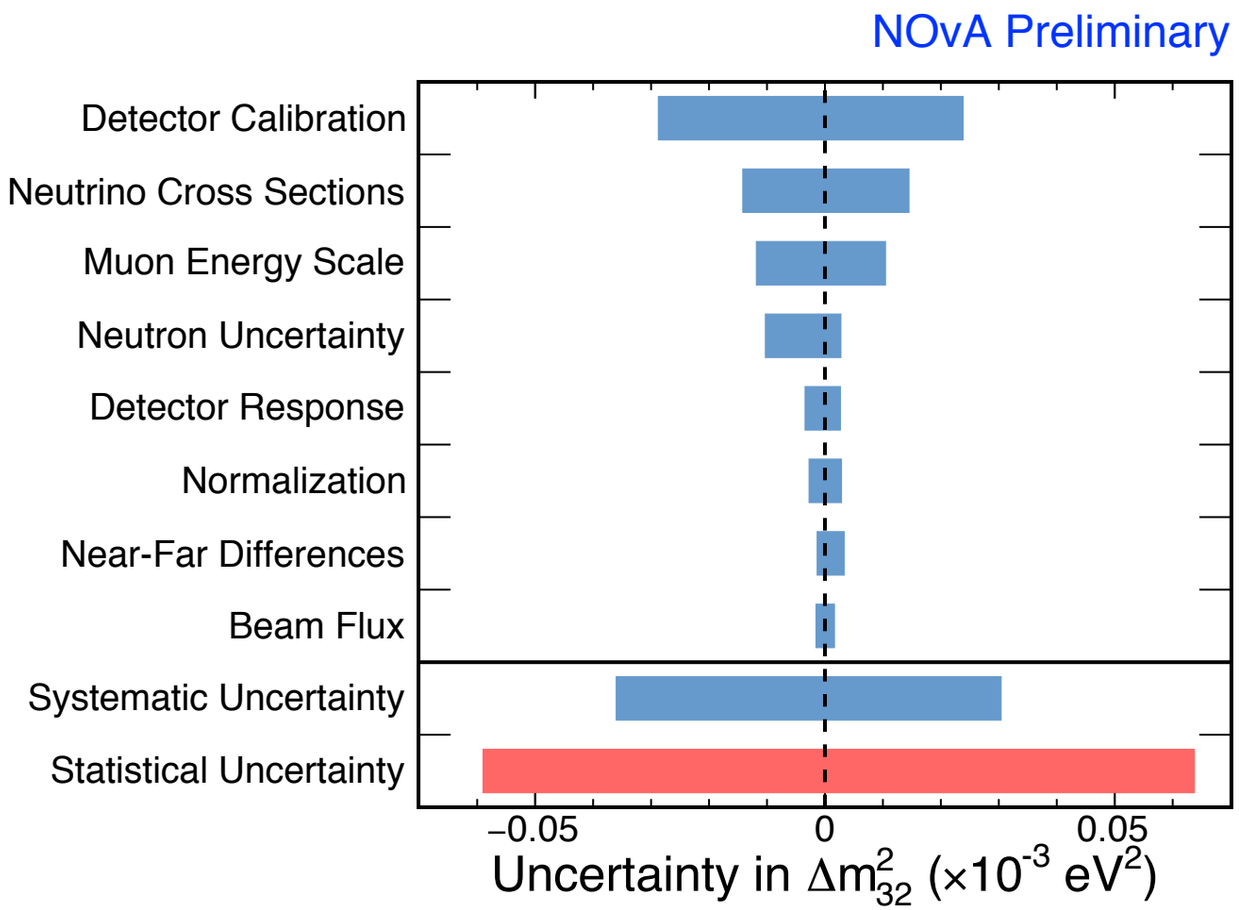
Extrapolation - Systematic Uncertainty

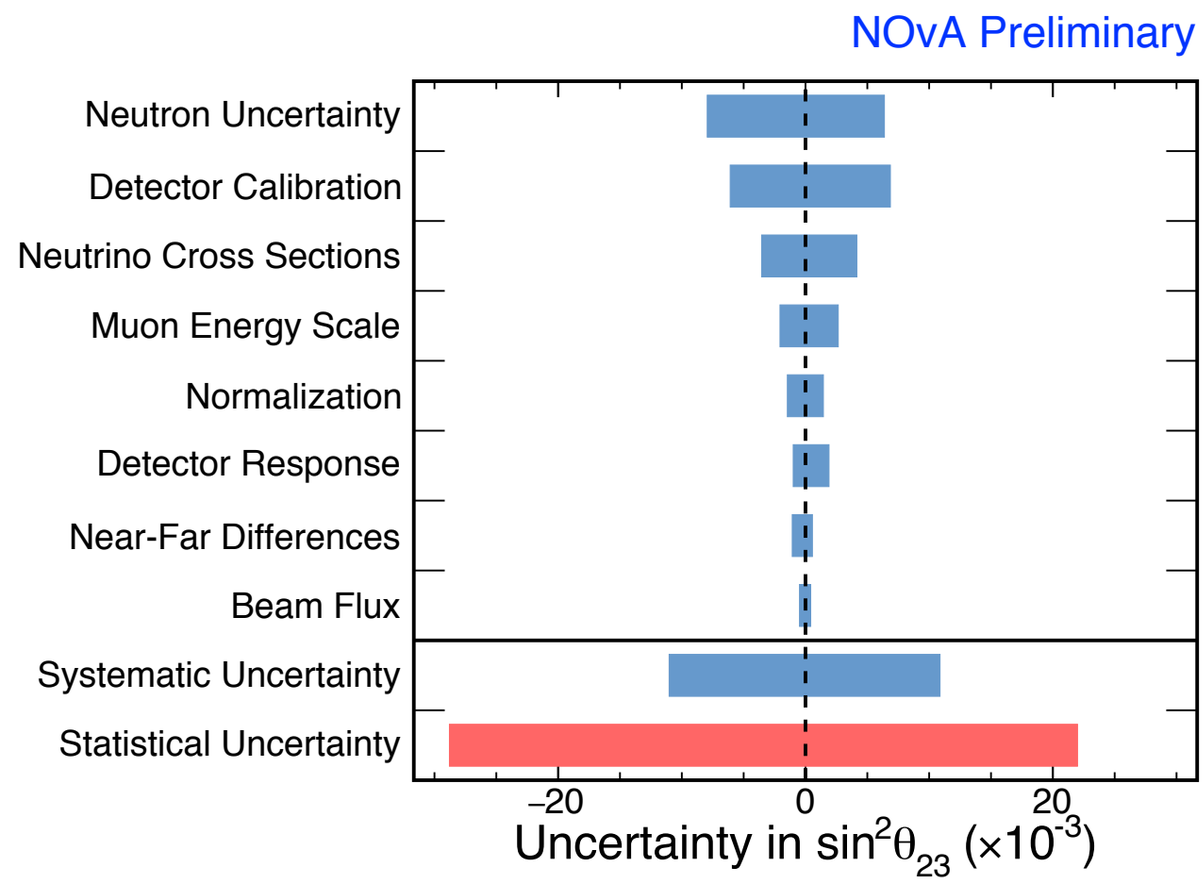
- Same extrapolation technique is used to extrapolate systematic uncertainty from the ND to the FD
- The ND data is replaced by the ND simulation under a systematic shift
- The systematically shifted simulation in the ND is then lead to the systematically shifted prediction in the FD
- Many of the systematic uncertainties cancels in the F/N ratios



Systematics in NOvA Analyses

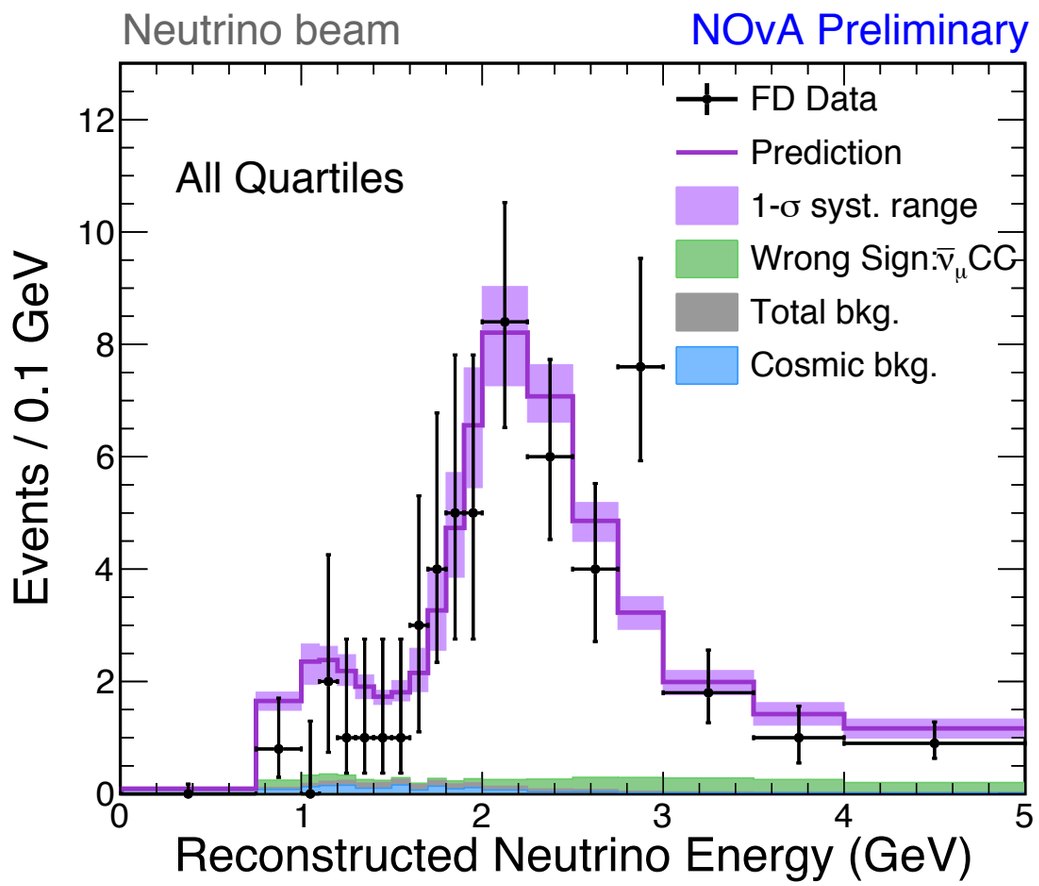
- Systematic uncertainties are included as nuisance parameters in the fit for all analyses

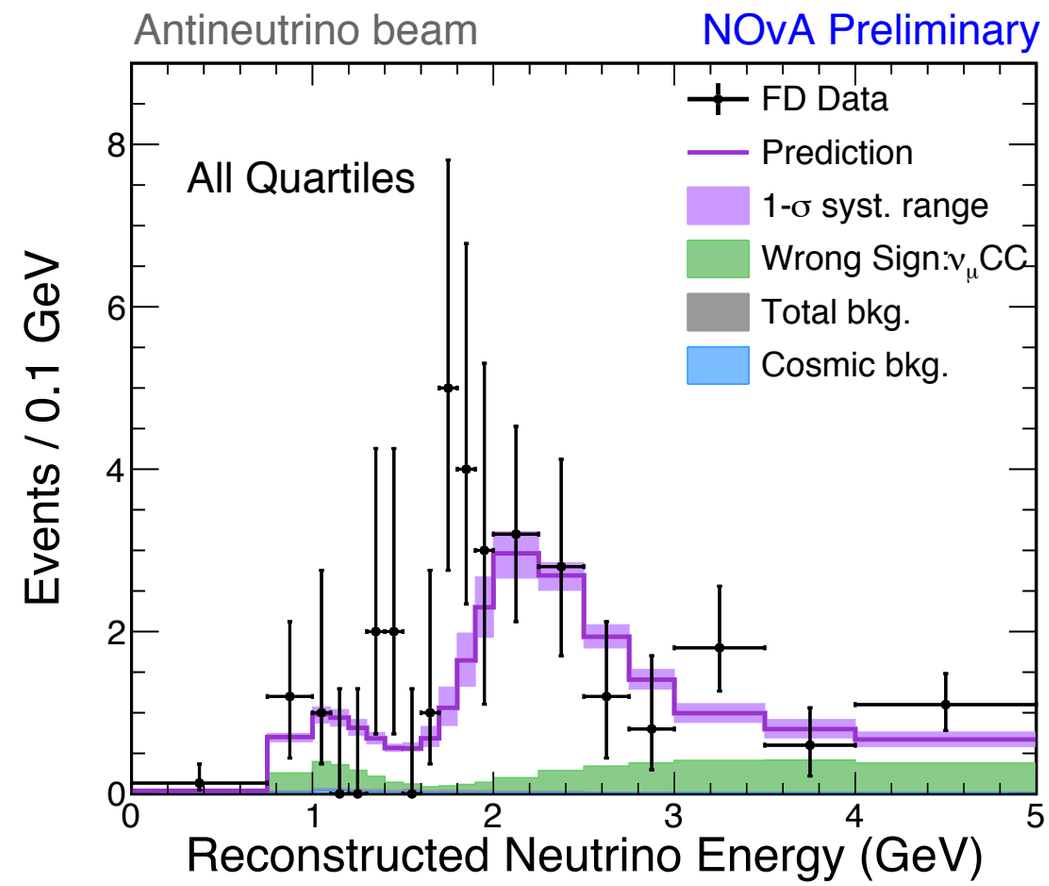




- The detector calibration and cross-section are two of the biggest systematics but we are still dominated by the statistical uncertainties

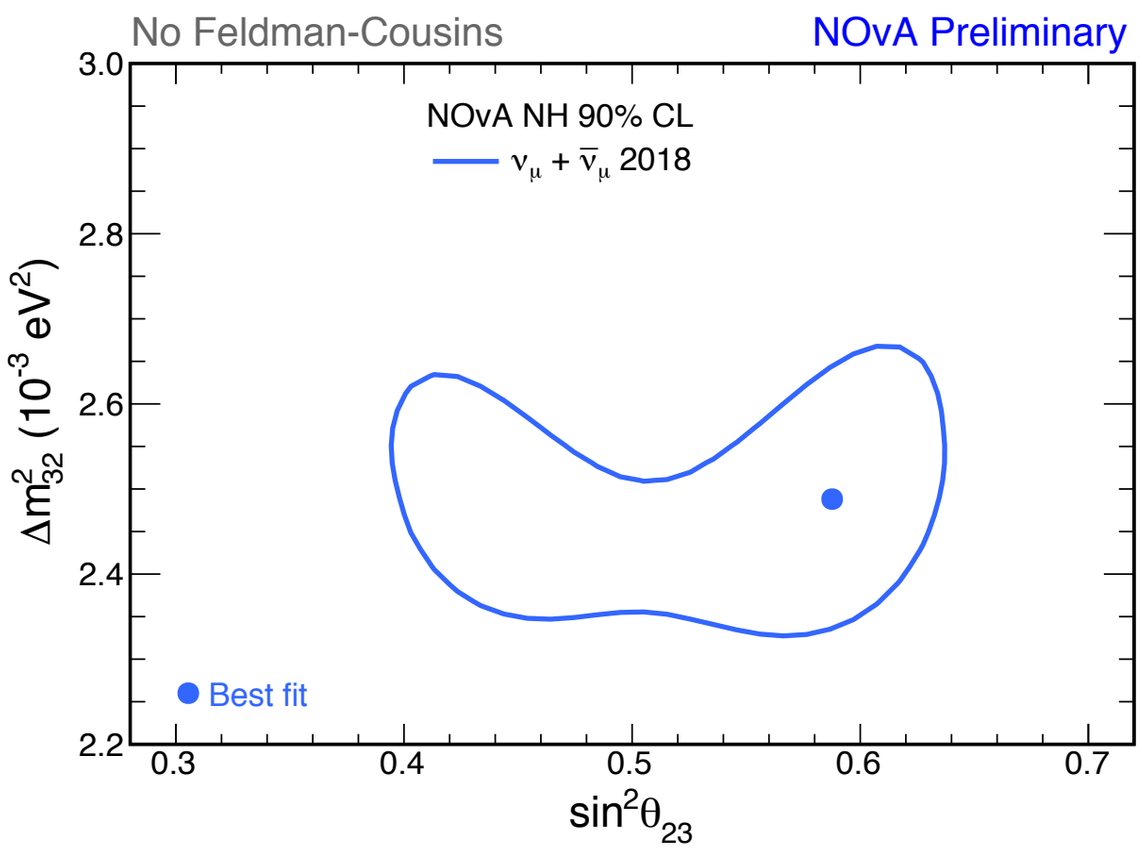
ν_μ FD Data Observation and Prediction

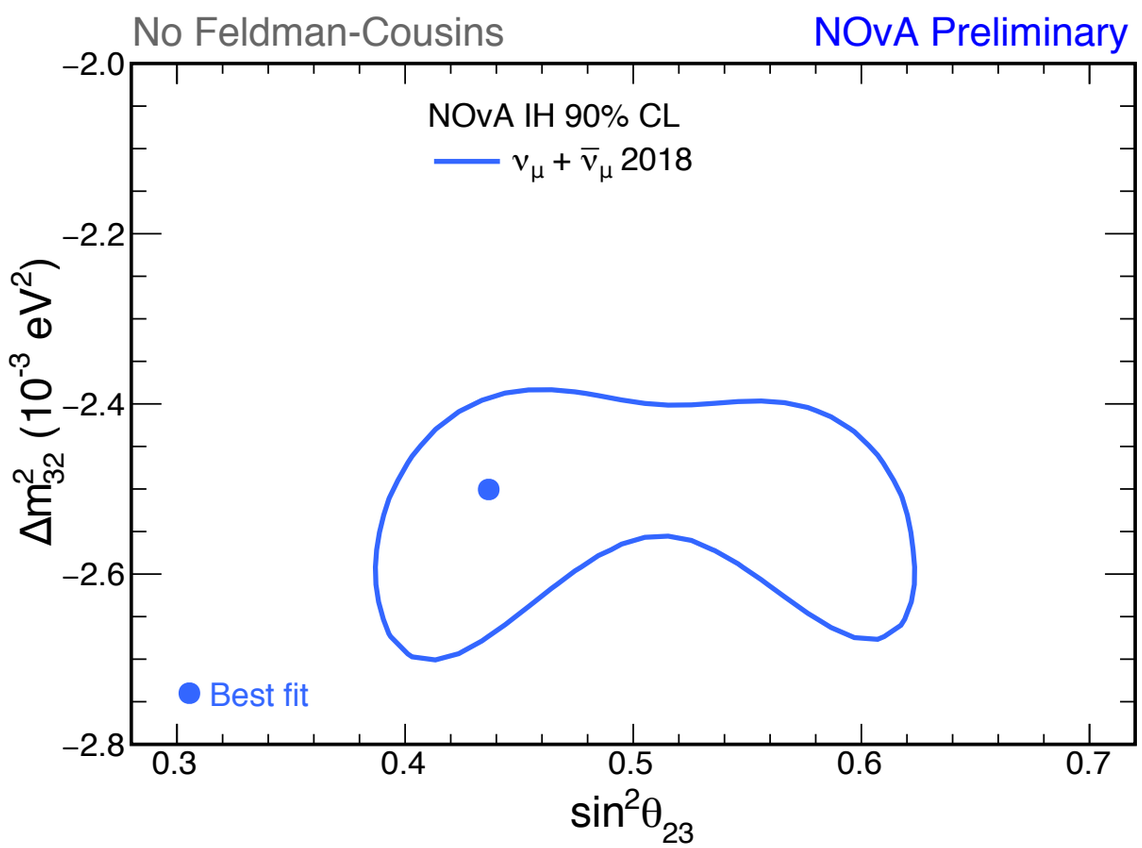




- Observe 113 events in the neutrino mode (expected 730 w/o oscillation) and 65 in the anti-neutrino mode (expected 266 w/o oscillation)
- Clear evidence of the oscillations

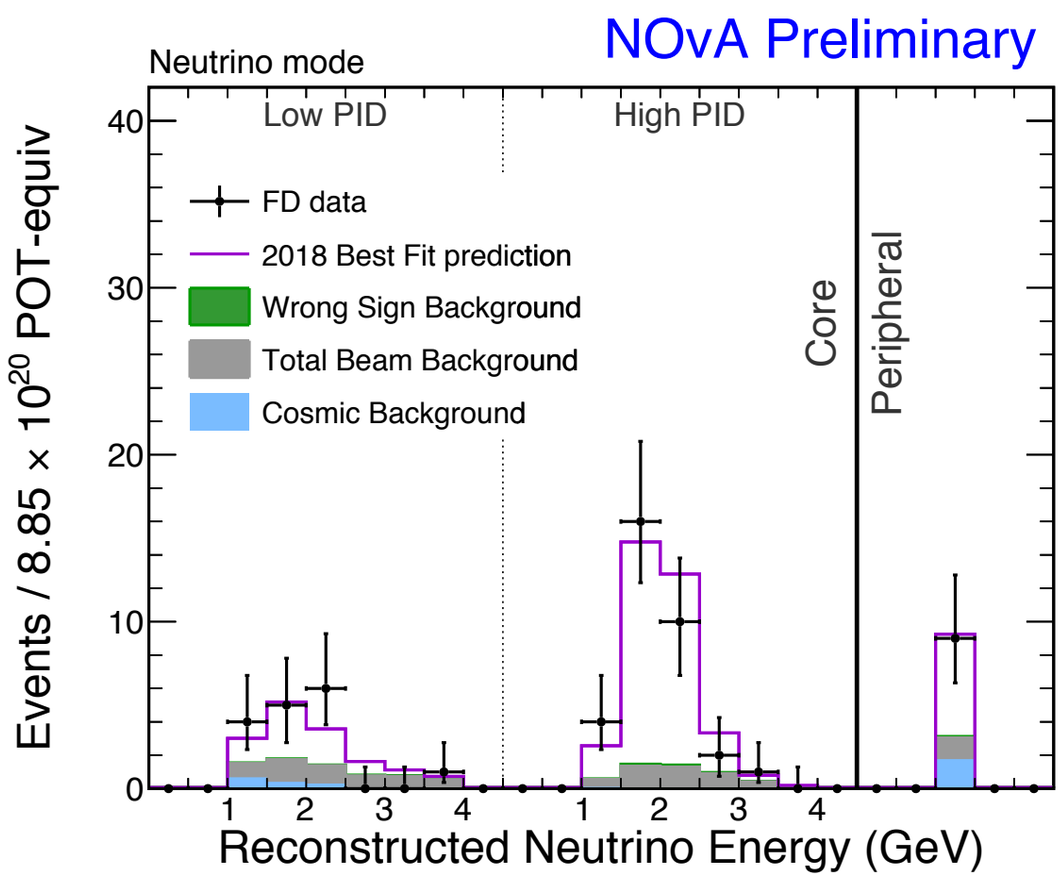
ν_μ Fit to the Disappearance Data

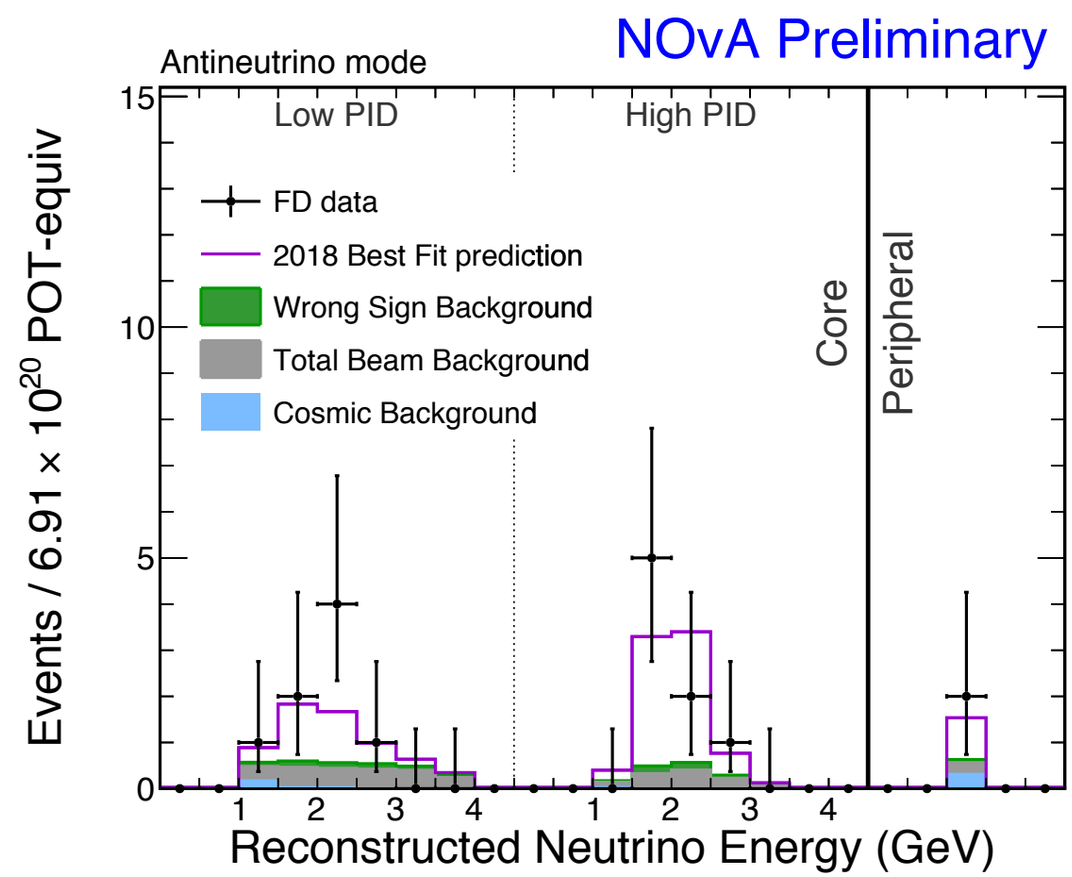




- Disappearance data is fitted for the Δm^2_{32} and $\sin^2\theta_{23}$ parameters
- At 90% C.L. the muon neutrino and anti-neutrino datasets prefer upper octant (UO; $\sin^2\theta_{23} > 0.5$) for the normal hierarchy (NH) and lower octant (LO; $\sin^2\theta_{23} < 0.5$) for the inverted hierarchy (IH)

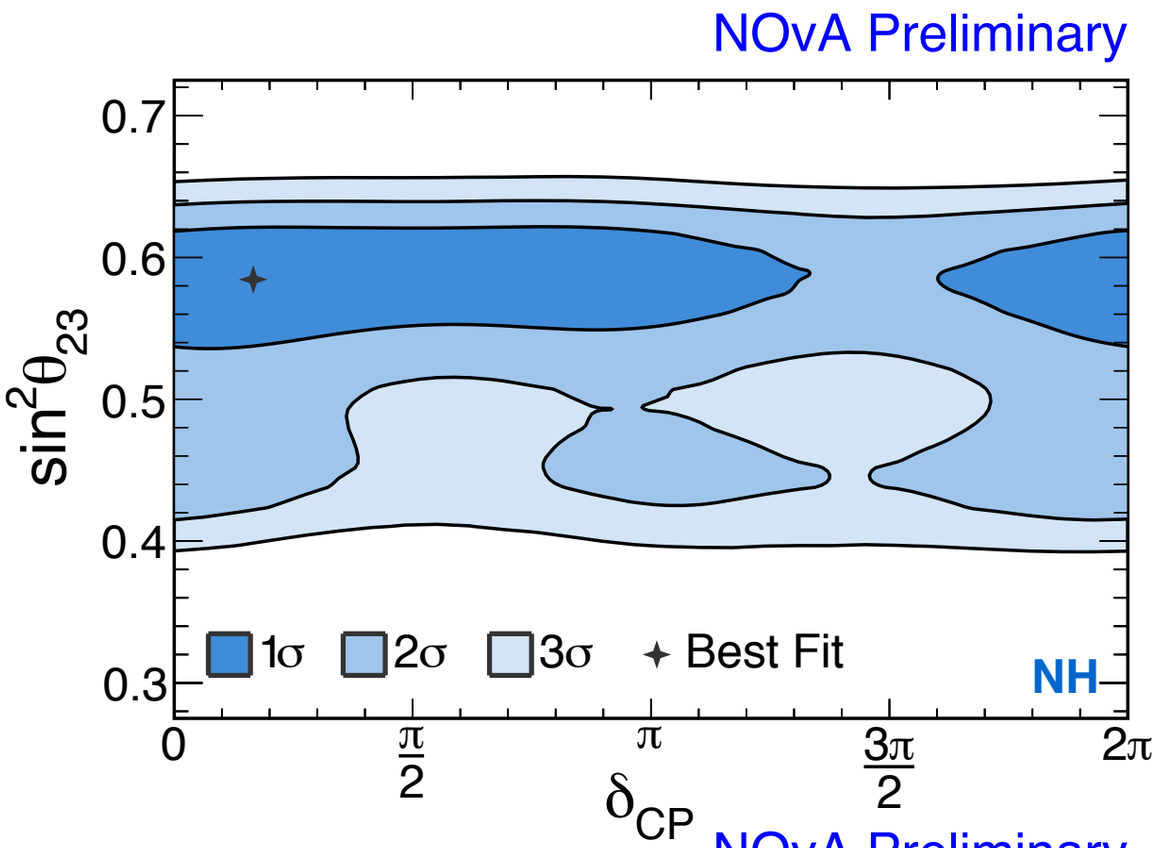
ν_e FD Data Observation and Prediction

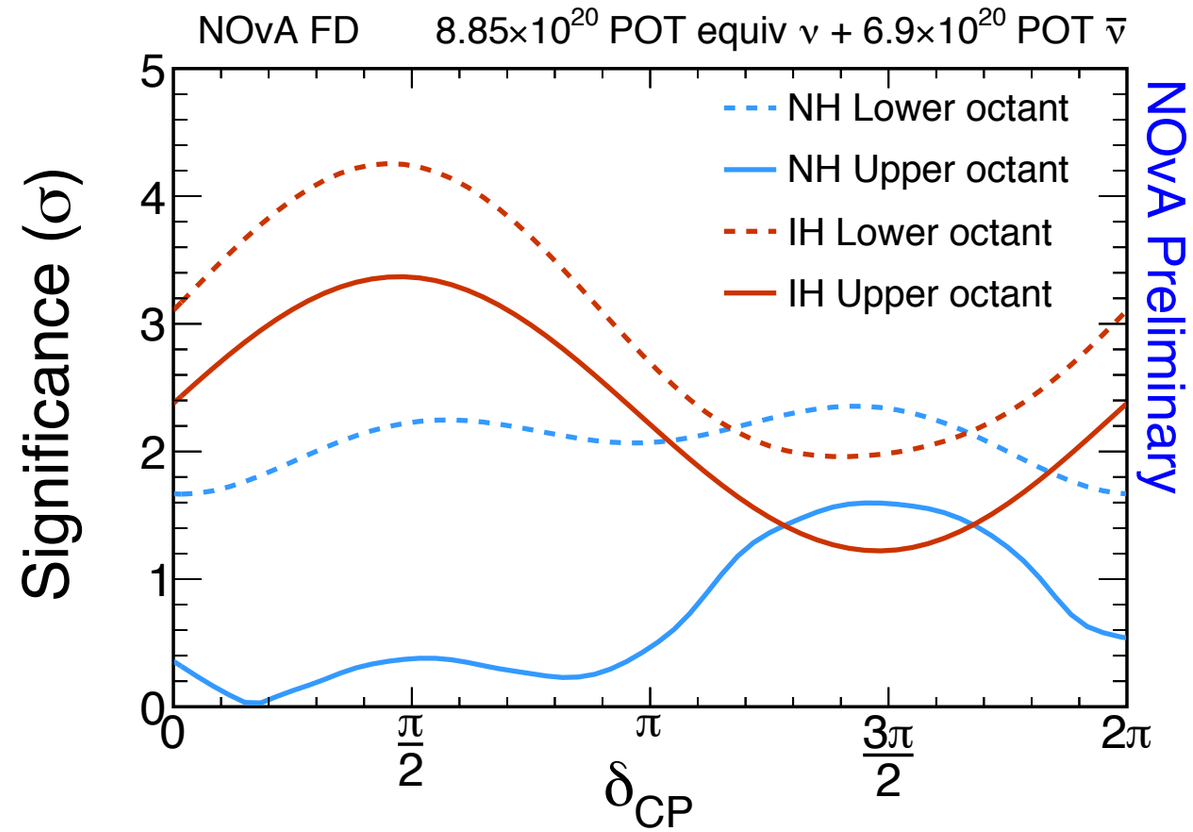


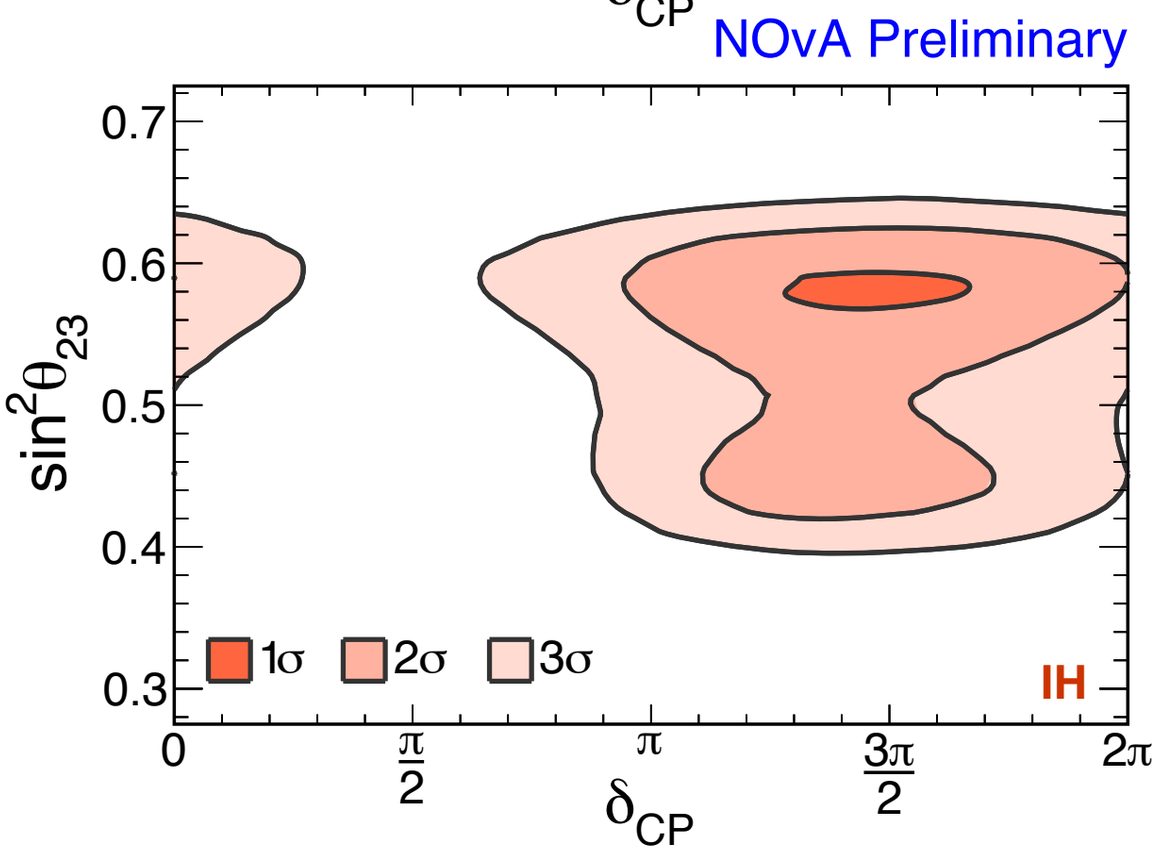


- Observe 58 events in the neutrino mode (expected 15 background events) and 18 in the anti-neutrino mode (expected 5.3 background events)
- Electron anti-neutrino appearance of > 4σ

Simultaneous Fit of the Disappearance and Appearance Data







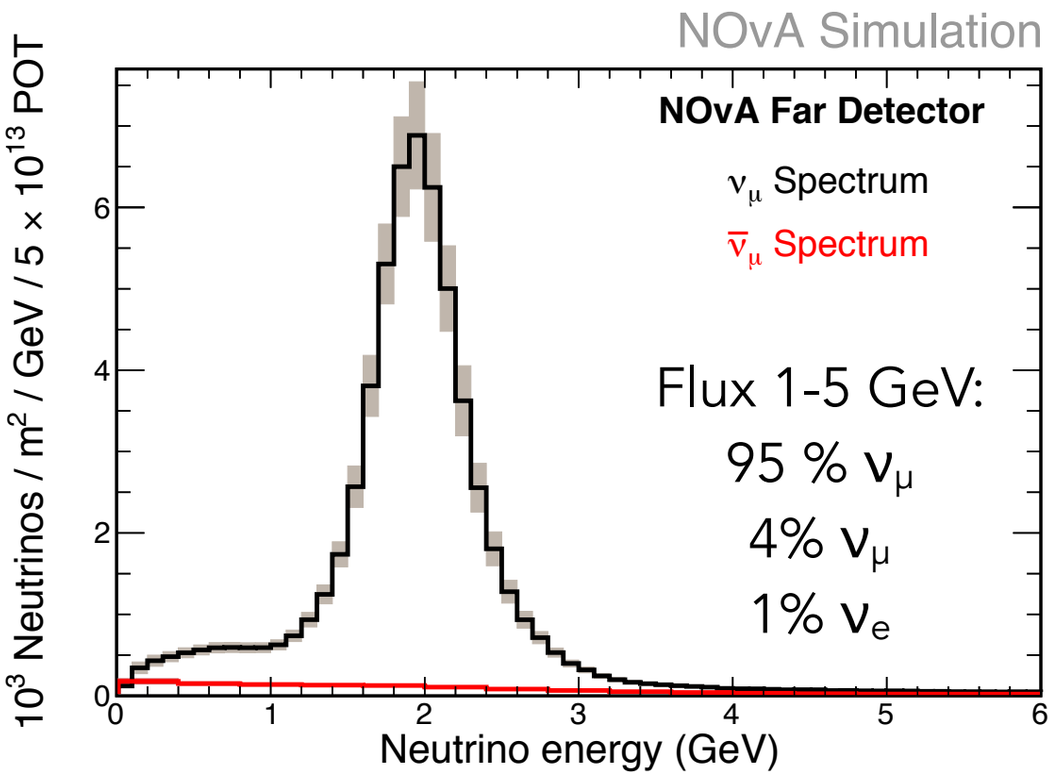
- Appearance Data is fitted for the $\sin^2\theta_{23}$ and δ_{cp} parameters
- Best Fit parameters
  - **δ_{cp} = 0.17π**
  - **$\sin^2\theta_{23}$ = 0.58 ± 0.03 (UO)**
  - **Δm^2_{32} = $(2.51^{+0.12}_{-0.08}).10^{-3}$ eV^2**
- Prefer NH at 1.8σ
- Exclude δ_{cp} = π/2 in the IH at >3σ

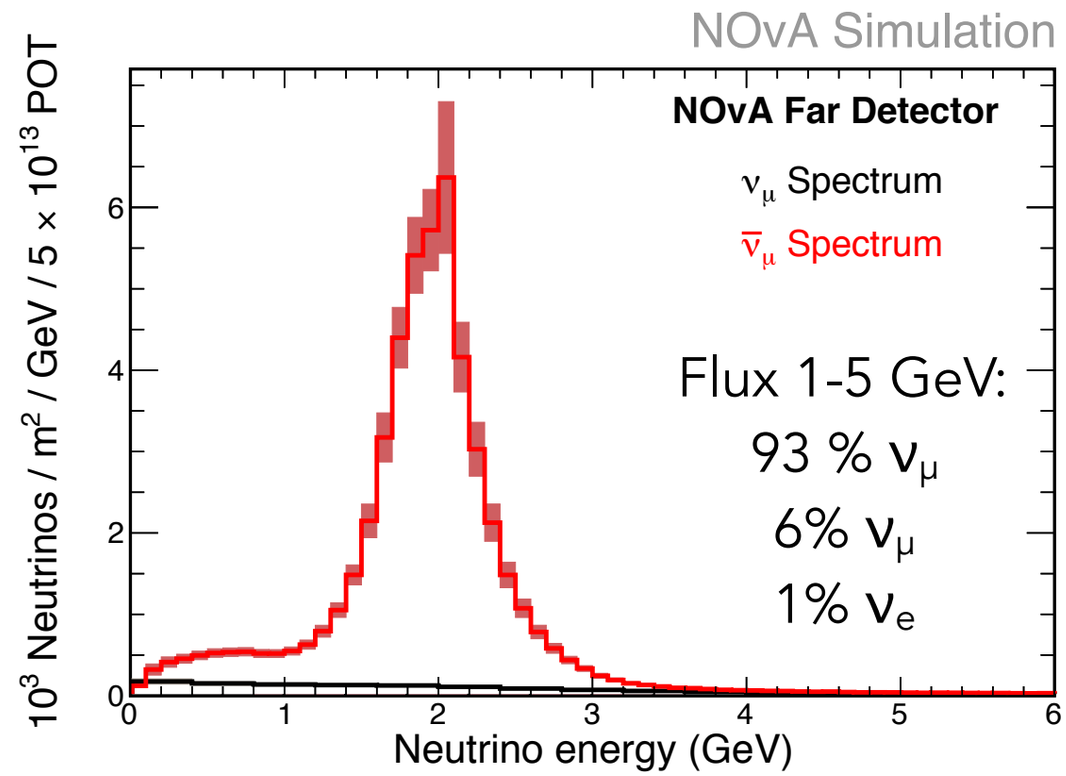
Summary

- NOvA is a two detector, long-baseline, accelerator based neutrino oscillation experiment
- The Near Detector measures NuMI beam before oscillations and helps in signal and background predictions in the Far Detector
- Having two functionally identical detectors is advantageous for cancelling uncertainties that are common between the two detectors
- Best fit to the ν_μ disappearance data prefer UO for the NH and LO for IH
- A simultaneous fit of the disappearance and appearance data prefer NH at 1.8σ and exclude $\delta_{cp} = \pi/2$ in the IH at >3σ

Backup

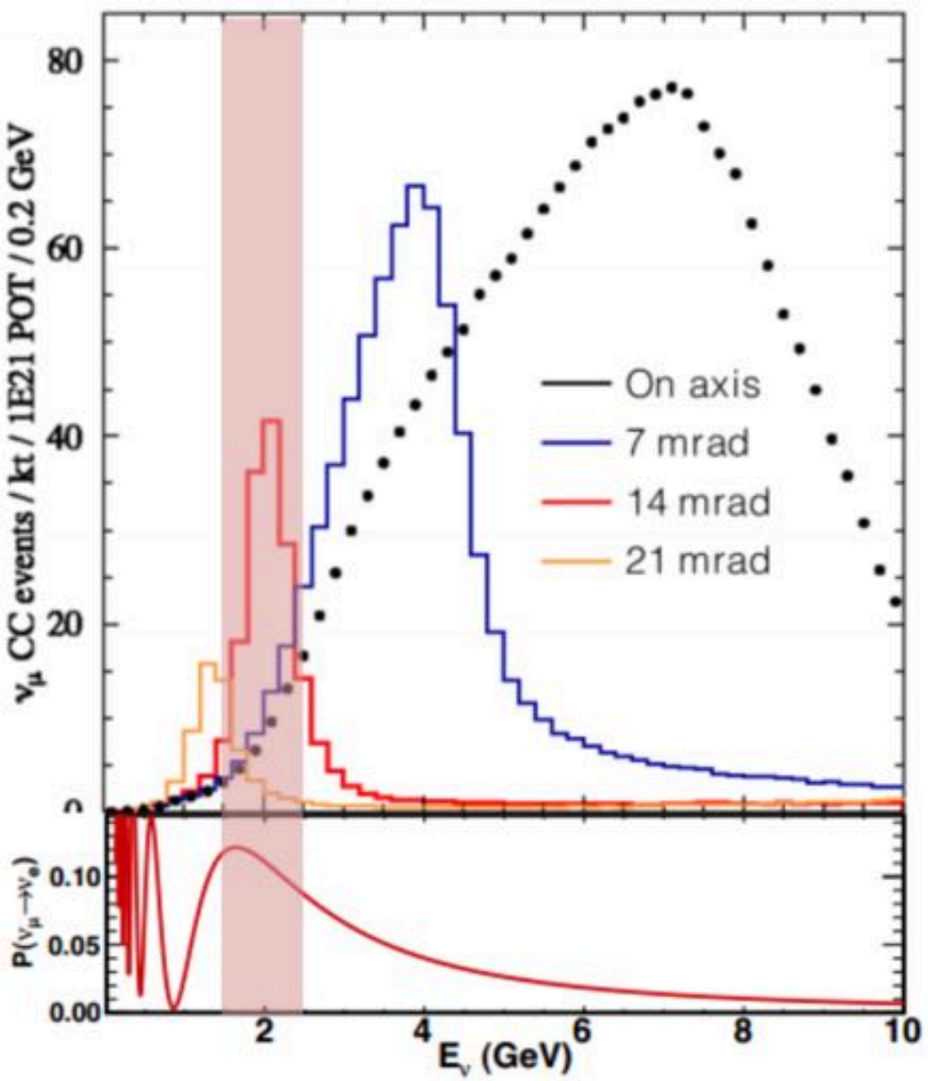
NuMI Beam Configuration

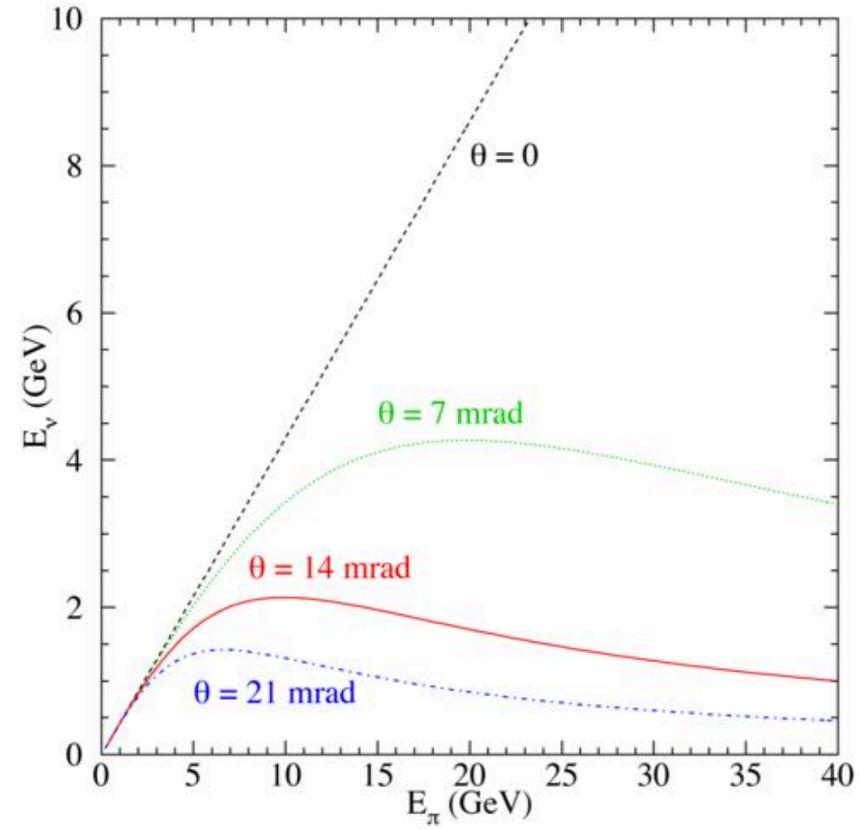




- The NuMI beam is 95% has ν_μ component in the neutrino beam mode and 93% $\bar{\nu}_\mu$ in the anti-neutrino beam mode

Off-axis configuration





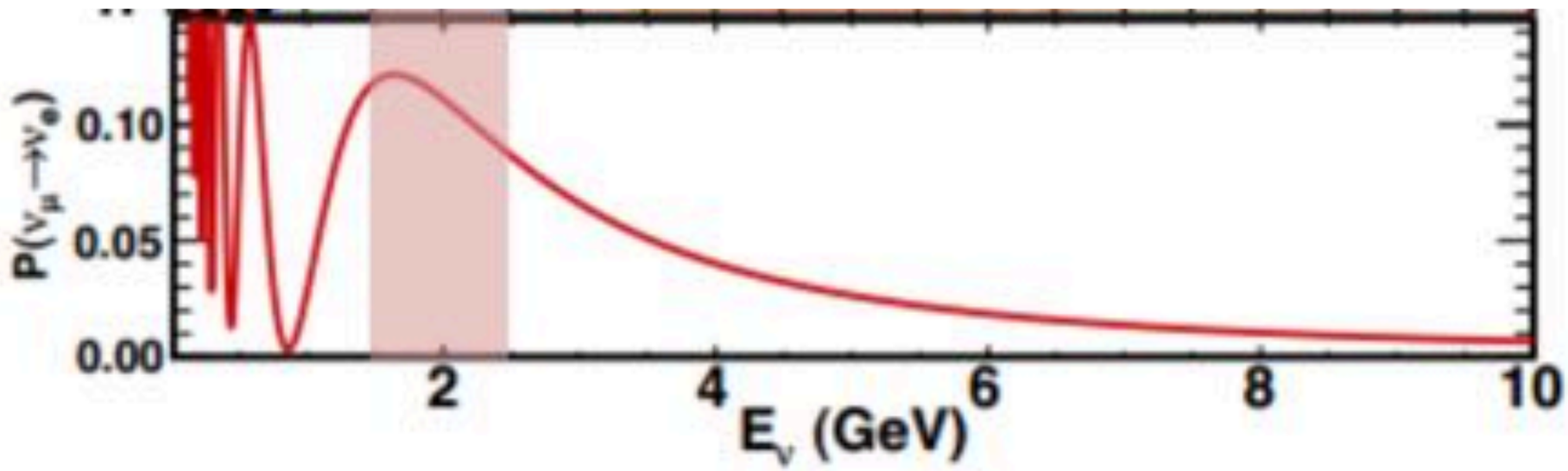
$$\pi^+ \to \mu^+ + \nu_\mu$$

$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}.$$

$$\gamma = \frac{E_\pi}{m_\pi}$$

- At 14.6 mrad off axis the neutrino spectrum becomes narrow, monochromatic around 2 GeV energy
- $\nu_\mu \longrightarrow \nu_e$ appearance probability maximizes near 2 GeV neutrino energy

$\nu_\mu \rightarrow \nu_e$ Appearance Oscillation Probability



$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$\Delta = \Delta m^2_{31} L/(4E) \qquad A = \overset{(-)}{+} G_f n_e L/(\sqrt{2}\Delta)$$

PMNS Matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

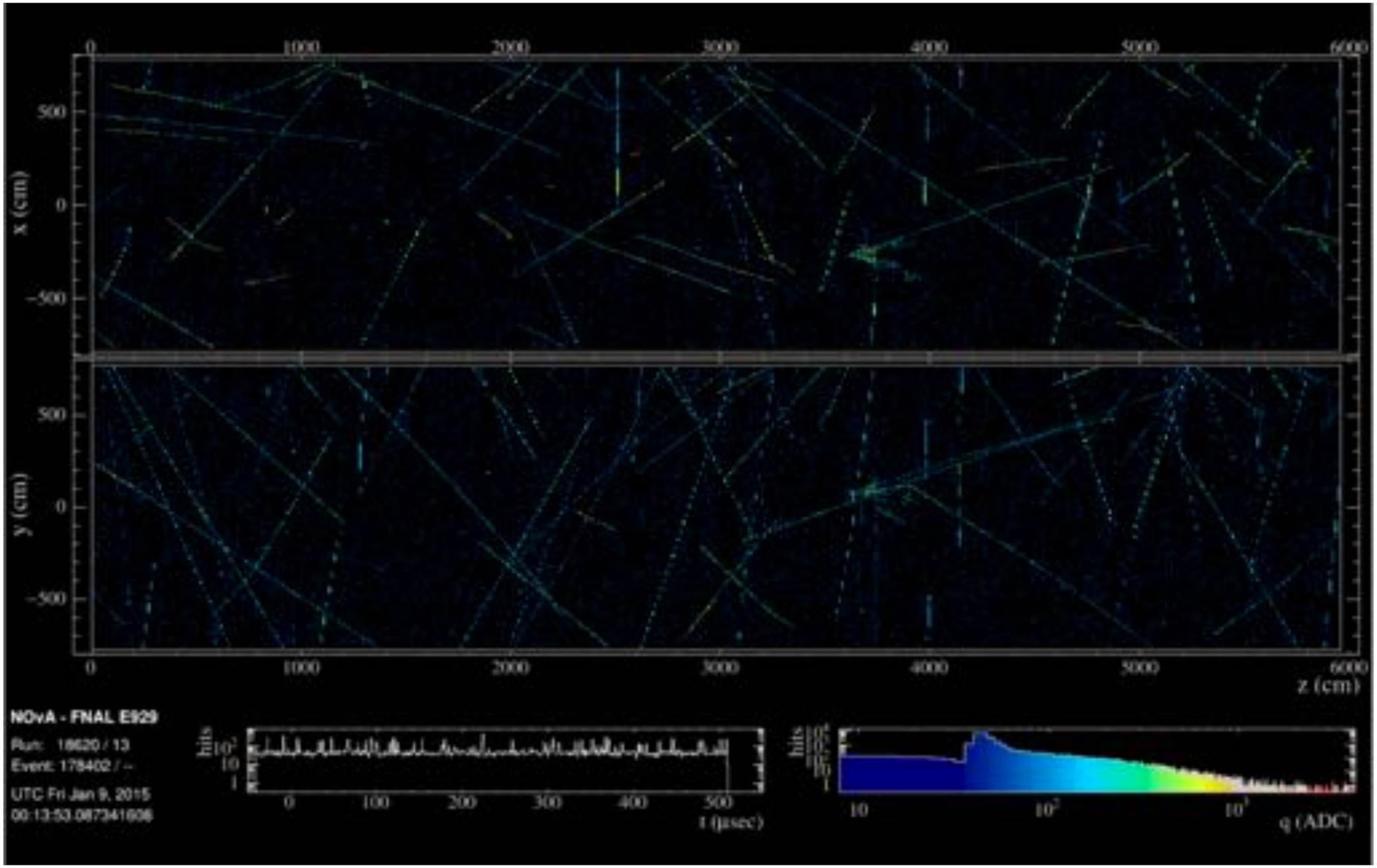
$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$\underset{-}{(+)}\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

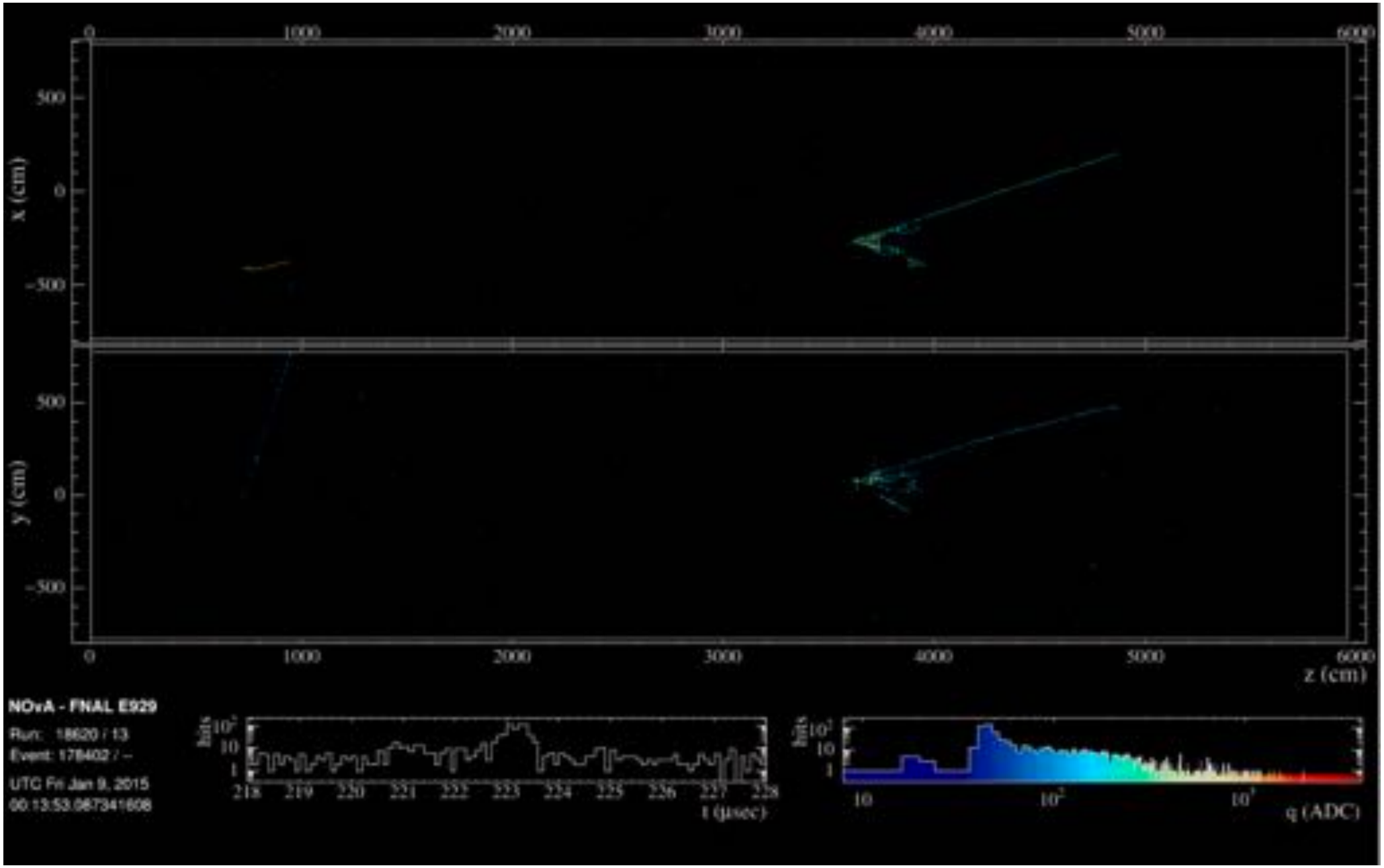
$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ $\quad \Delta = \Delta m^2_{31} L/(4E)$ $\quad A = \overset{(-)}{+} G_F n_e L/(\sqrt{2}\Delta)$

Cosmic Events



Neutrino Event

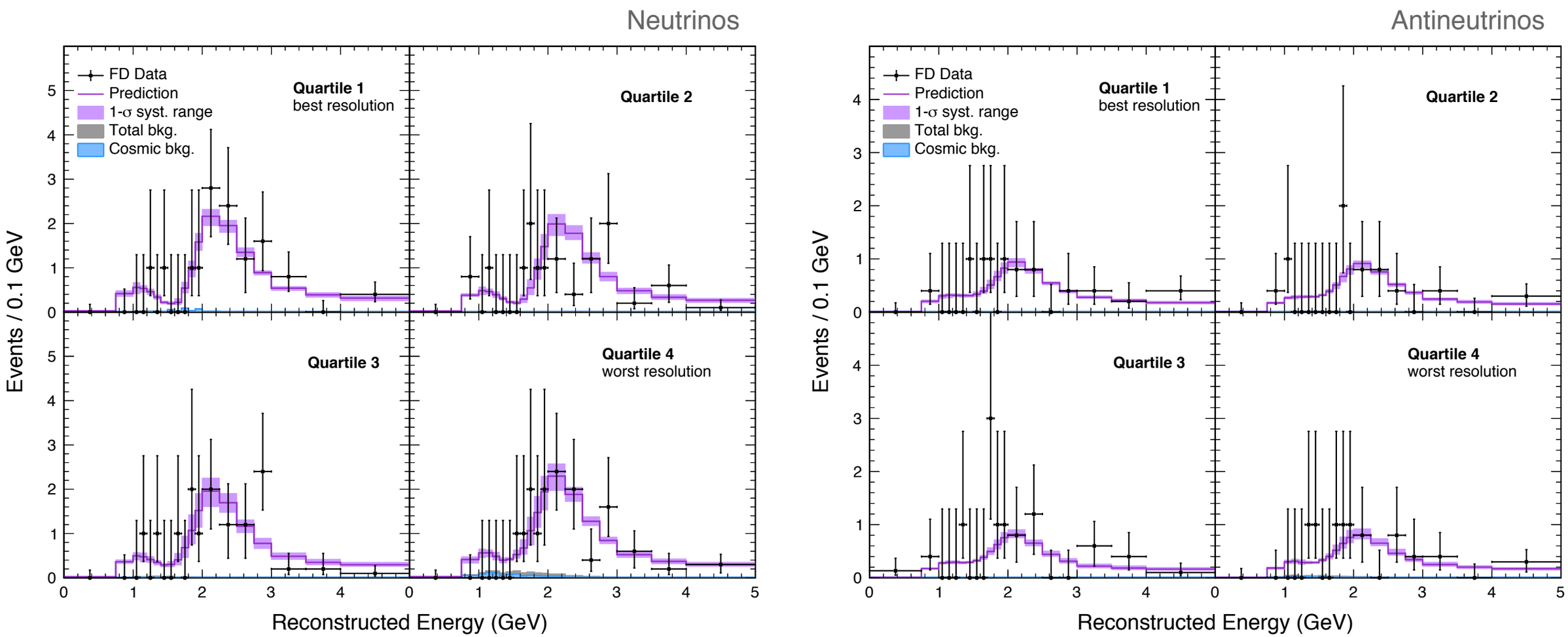


Systematics

Source of Uncertainty	$\sin^2\theta_{23}$ ($\times 10^{-3}$)	δ_{CP}/π	Δm^2_{32} ($\times 10^{-3}$ eV^2)
Beam Flux	+0.42 / -0.48	+0.0088 / -0.0048	+0.0016 / -0.0015
Detector Calibration	+6.9 / -6.1	+0.15 / -0.023	+0.024 / -0.029
Detector Response	+1.9 / -0.99	+0.055 / -0.054	+0.0027 / -0.0034
Muon Energy Scale	+2.6 / -2.1	+0.015 / -0.0026	+0.01 / -0.012
Near-Far Differences	+0.56 / -1.1	+0.11 / -0.064	+0.0033 / -0.0013
Neutrino Cross Sections	+4.2 / -3.5	+0.085 / -0.072	+0.015 / -0.014
Neutron Uncertainty	+6.4 / -7.9	+0.002 / -0.0052	+0.0028 / -0.01
Normalization	+1.4 / -1.5	+0.031 / -0.024	+0.0029 / -0.0027
Systematic Uncertainty	+9.6 / -11	+0.21 / -0.11	+0.032 / -0.035
Statistical Uncertainty	+22 / -29	+0.9 / -0.27	+0.064 / -0.059

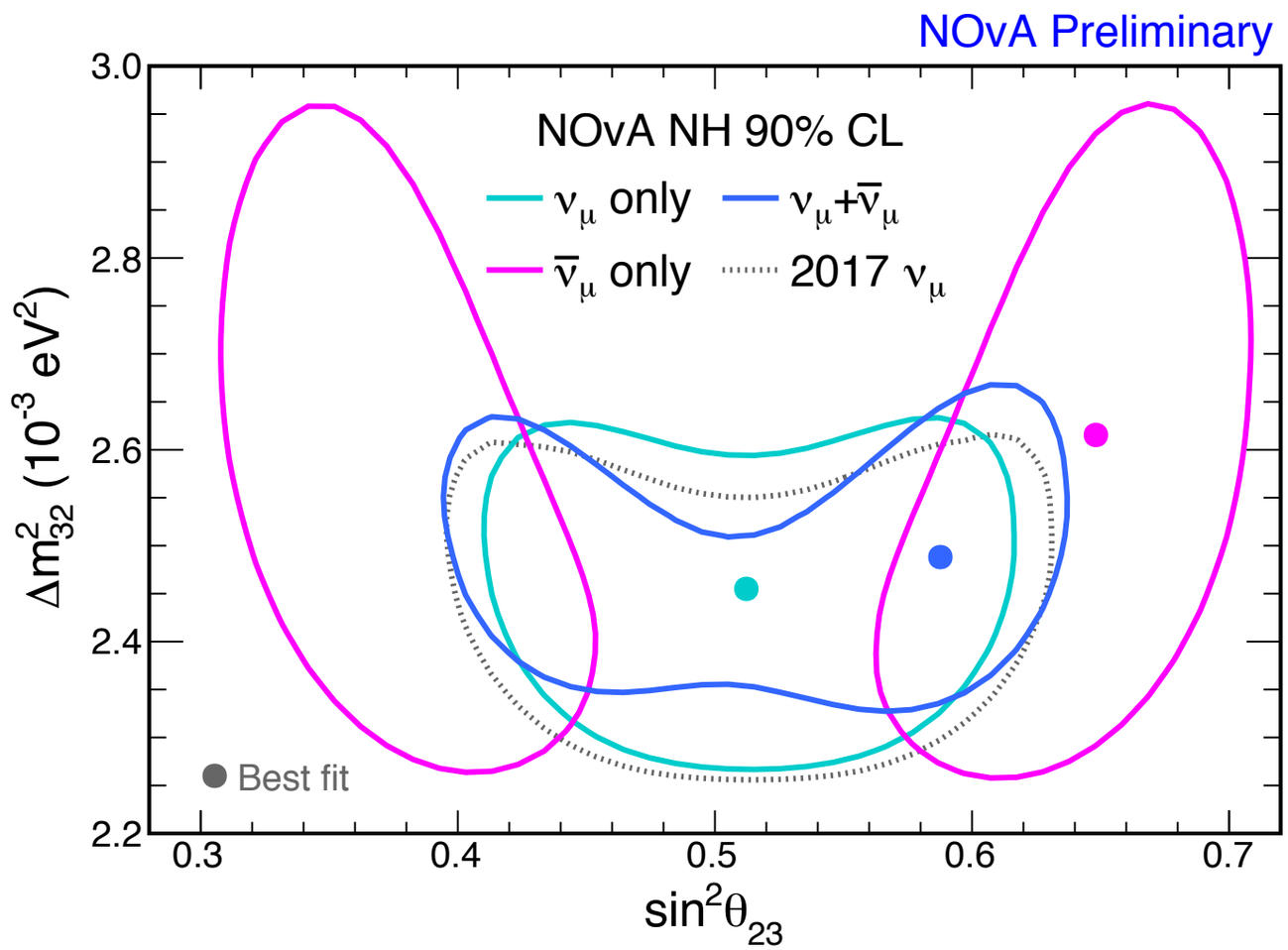
- The detector calibration and cross-section are two of the biggest systematics but we are still dominated by the statistical uncertainties

FD ν_μ Data in all Quartiles



- Neutrino and anti neutrino data are divided into different quartiles based on the hadronic energy fraction in the total reconstructed neutrino energy

ν_μ Fit to the Neutrino and Anti-neutrino Data

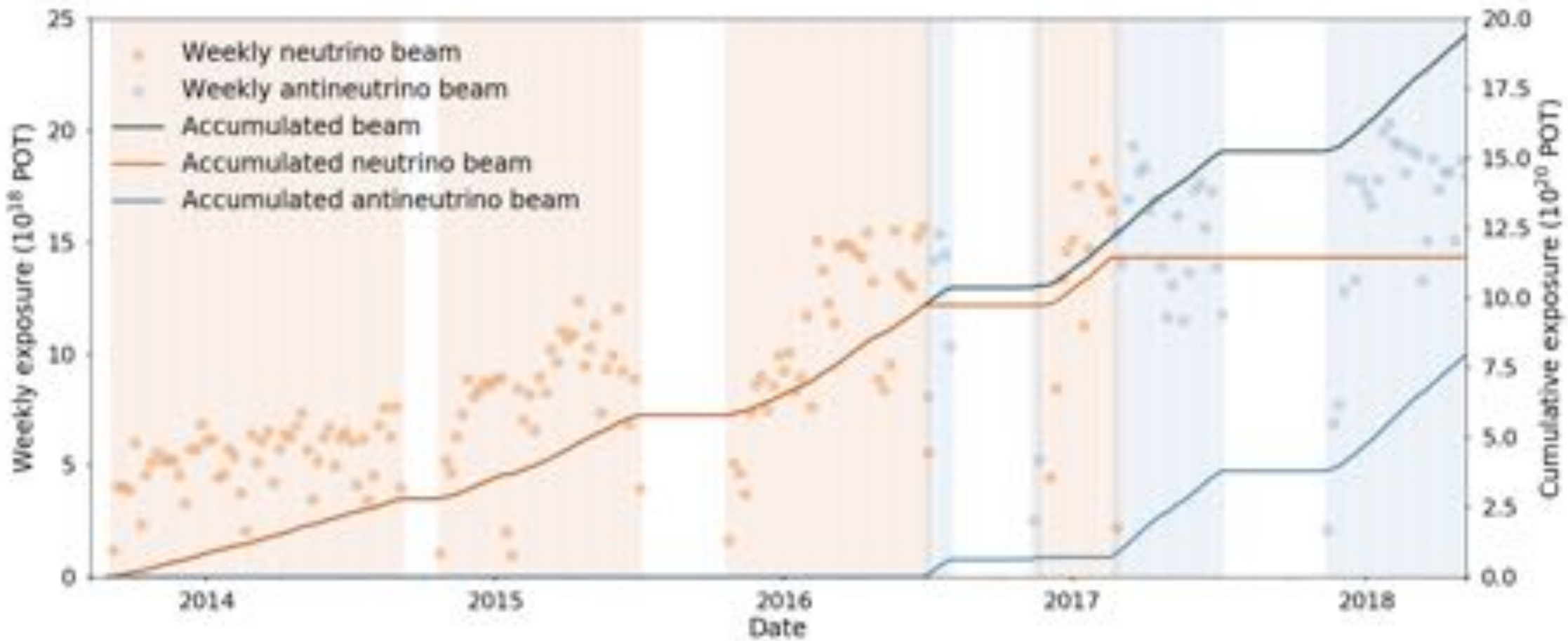


- The contours for the ν_μ and $\bar{\nu}_\mu$ data are shown

χ^2 Fit

$$\chi_i^2 = 2 \times \left(F_i^{Predicted} - F_i^{Data} + F_i^{Data} \ln \frac{F_i^{Data}}{F_i^{Predicted}} \right)$$

Beam Period



- 8.85e20 neutrino POT from February 2014 to February 2017
- 6.9e20 anti-neutrino POT from February 2017 to April 2018

Neutrino Interactions