Recent Searches for Sterile Neutrinos with NOvA

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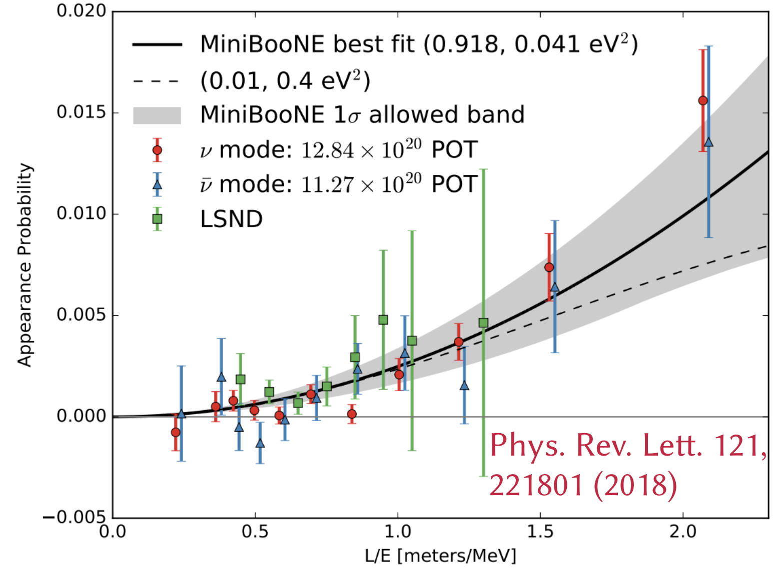
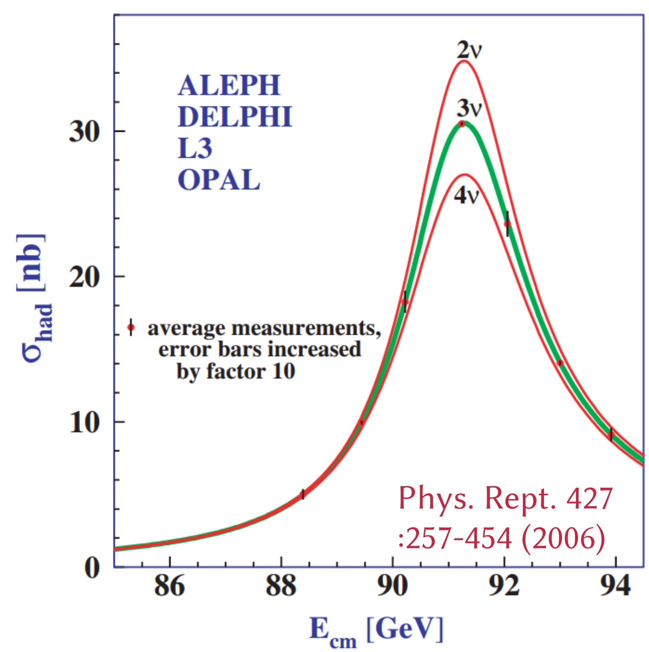
Sterile Neutrinos

- Short-baseline experiments (LSND, MiniBooNE) observed anomalous excesses of ν_e ($\bar{\nu}_e$) appearance in ν_μ ($\bar{\nu}_\mu$) beams
- Observed rate from calibration sources used at gallium radiochemical solar neutrino experiments produced results consistent with ν_e or $\bar{\nu}_e$ disappearance over short baselines
- The anomalies could all be explained by oscillations driven by a mass splitting $\Delta m^2 \sim 1$ eV^2
  - Not consistent with three known flavors
- Measurement of Z decays at LEP only allows for three light active neutrinos
  - Any extra light neutrino must be sterile



Phys. Rev. Lett. 121, 221801 (2018)

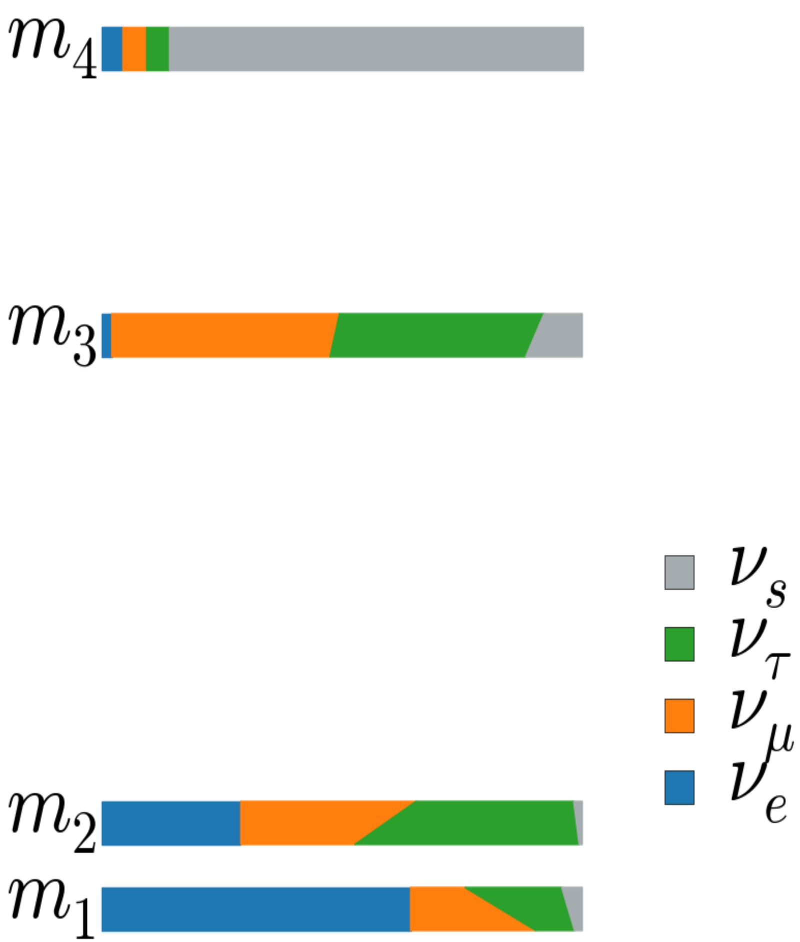


Phys. Rept. 427 :257-454 (2006)

3+1 Model

- Simplest model adds one sterile neutrino
- Expand PMNS matrix from 3x3 ⟶ 4x4
- 6 new parameters
  - One mass scale (Δm^2_{41})
  - Three mixing angles (θ_{14}, θ_{24}, θ_{34})
  - Two CP-violating phases (δ_{14}, δ_{24})

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$



Search for Sterile Neutrinos Using Neutral Currents

- Neutral current interaction rate is the same for 3 active neutrinos
  - NC rate is insensitive to 3 flavor oscillations
- Sterile neutrino do not interact in the detector
  - $\nu_\mu \longrightarrow \nu_s$ reduce the NC rate at the FD
- One oscillation term for $\nu_\mu \longrightarrow \nu_s$ oscillations at atmospheric frequency
- Narrow-band beam was optimized to produce events with energies very close to atmospheric maximum

$$
\begin{aligned}
&1 - P(\nu_\mu \to \nu_s) \approx \\
&1 - 4\left|U_{\mu 3}\right|^2 \left|U_{s3}\right|^2 \sin^2 \Delta_{31} \\
&\quad - 4\left|U_{\mu 4}\right|^2 \left|U_{s4}\right|^2 \sin^2 \Delta_{41} \\
&\quad - 8\,\mathrm{Re}\left(Z\right) \sin \Delta_{31} \cos \Delta_{43} \sin \Delta_{41} \\
&\quad - 8\,\mathrm{Im}\left(Z\right) \sin \Delta_{31} \sin \Delta_{43} \sin \Delta_{41} \\
&Z = U^*_{\mu 4} U_{s4} U_{\mu 3} U^*_{s3}
\end{aligned}
$$

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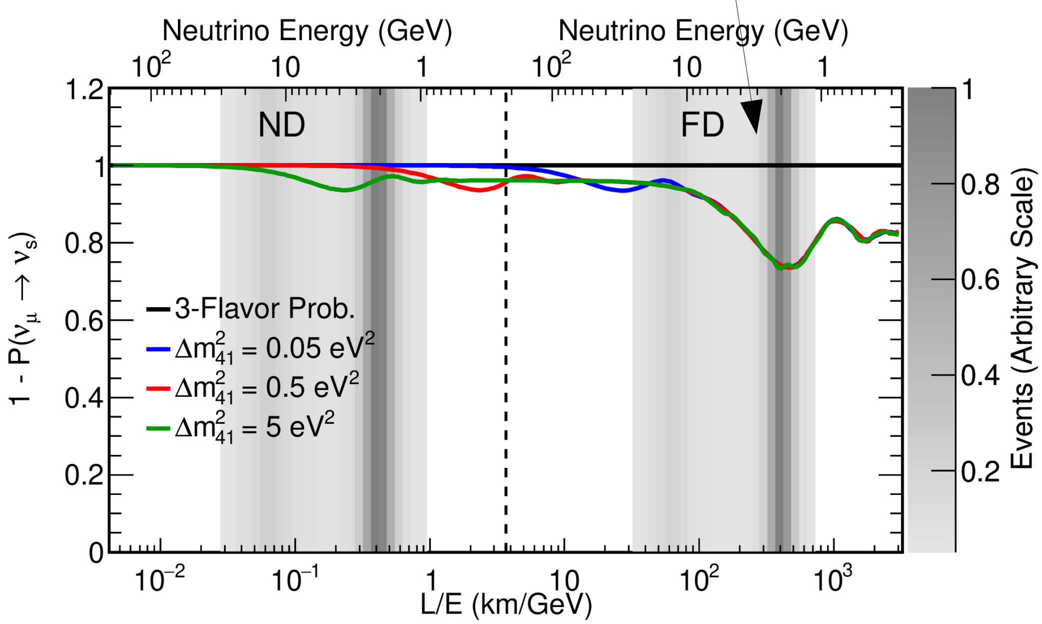
- Narrow-band beam was optimized to produce events with energies very close to atmospheric maximum
- Search in $0.05\ \text{eV}^2 < \Delta m^2_{41} < 0.5\ \text{eV}^2$
  - No significant ND oscillations
  - Rapid oscillations at FD $\to$ no Δm^2_{41} dependence

$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \frac{1}{2}\cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24} + \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31} - \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}\sin 2\Delta_{31}$$

Rapid oscillation approximation (exact formula used for fitting)



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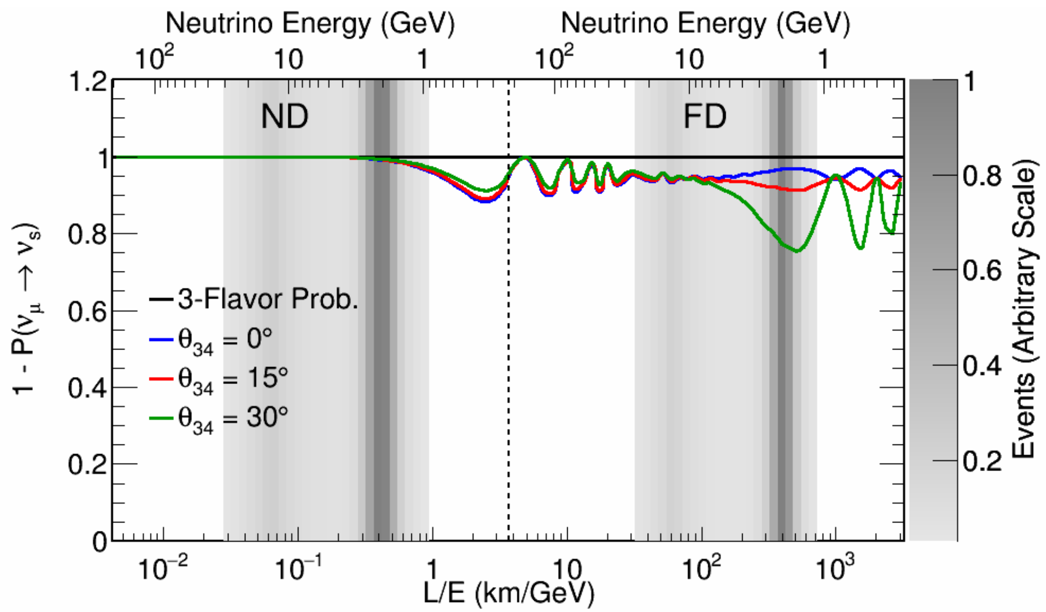
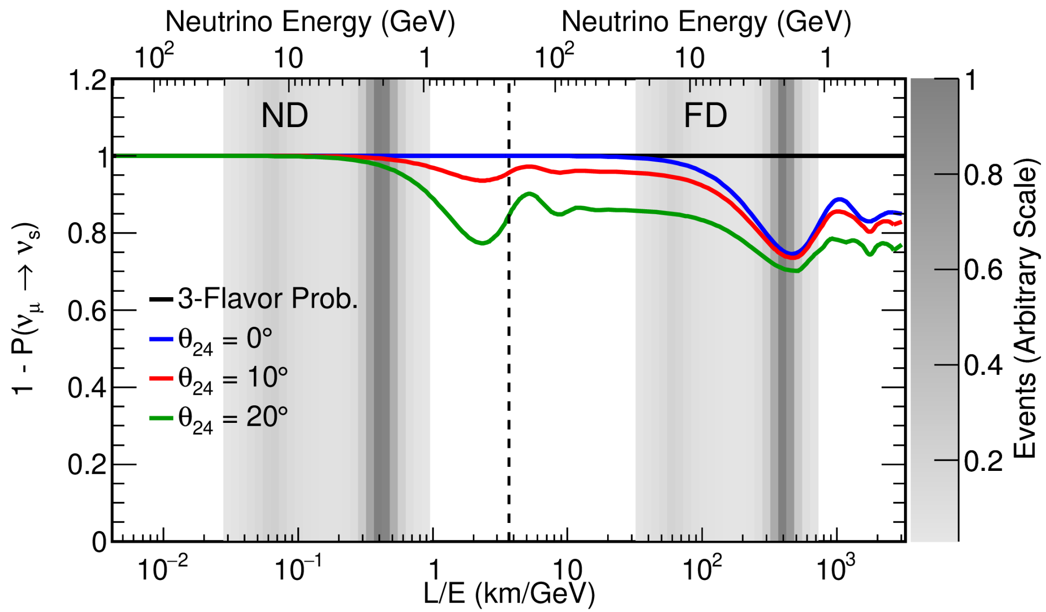
- Narrow-band beam was optimized to produce events with energies very close to atmospheric maximum
- Depth of oscillations at the oscillation maximum is primarily controlled by θ_{34}
- θ_{24} changes the high energy tail





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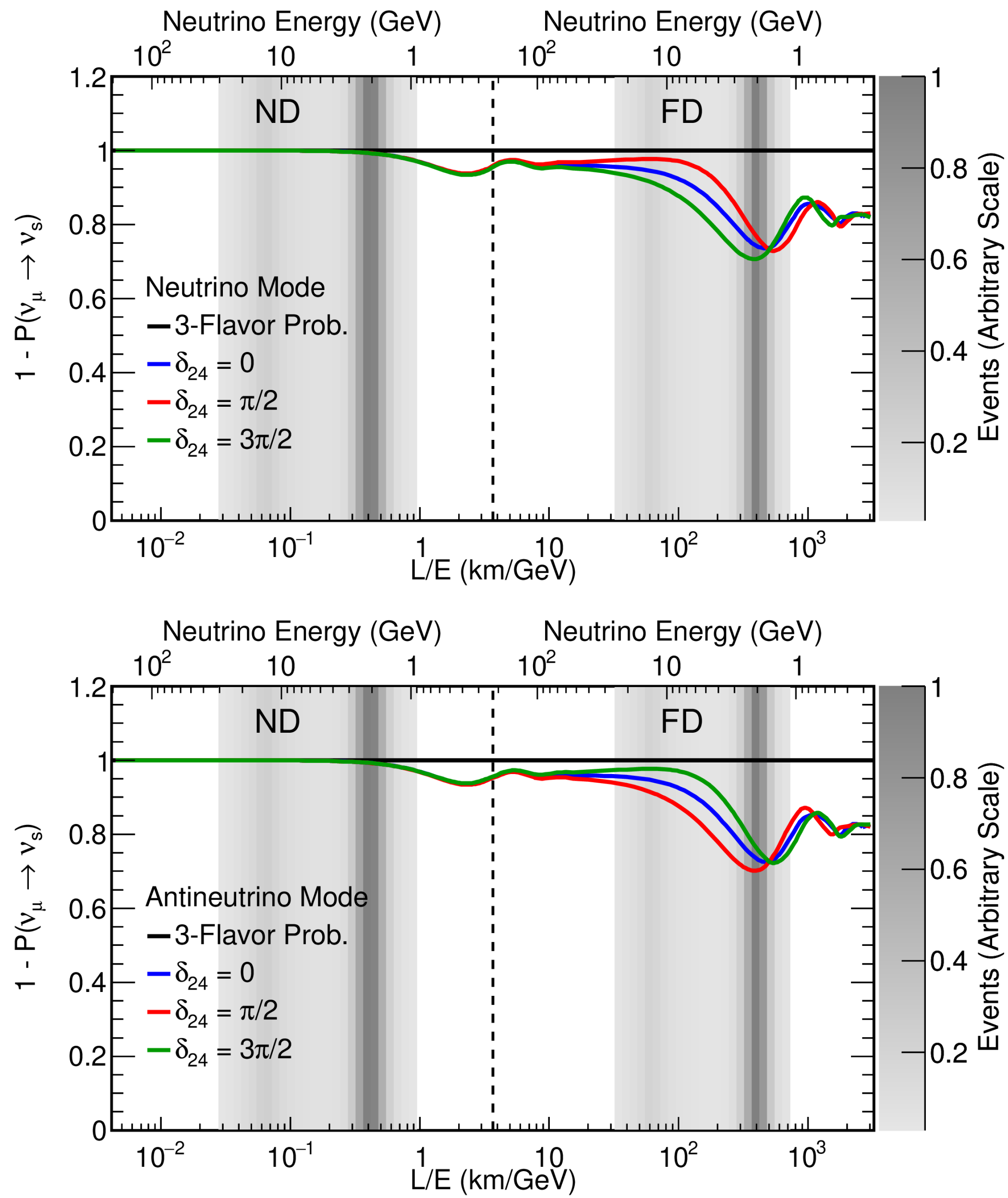
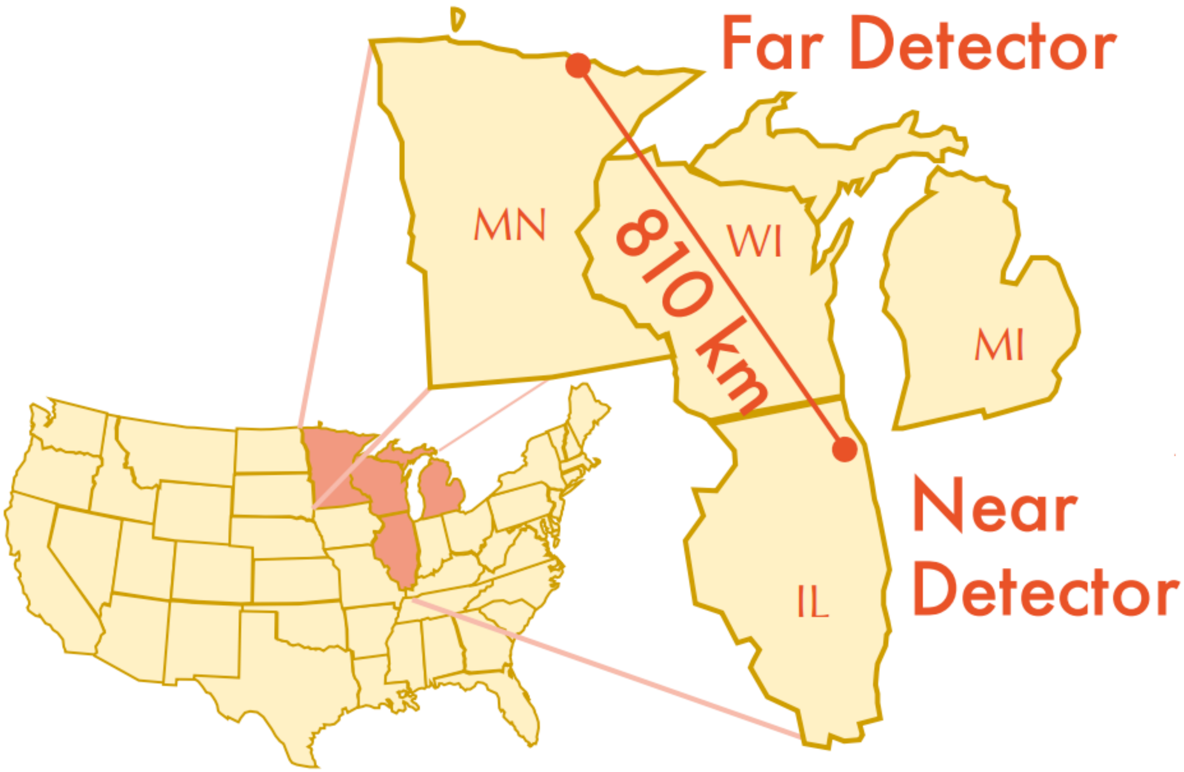
- One oscillation term for $\nu_\mu \rightarrow \nu_s$ oscillations at atmospheric frequency
- Narrow-band beam was optimized to produce events with energies very close to atmospheric maximum
- The CP-violating phase, δ_{24}, shifts the disappearance maximum, compensating for θ_{24} and θ_{34} effects
  - Shifts are reversed in neutrino and antineutrino running
    - Analyzing both modes can provide extra constraints and help disentangle oscillations and systematics



NuMI Off-Axis ν_e Appearance Experiment

NOvA is a long-baseline neutrino oscillation experiment located 14 mrad off-axis from the NuMI beam designed to measure:



ν_e appearance

- Mass hierarchy
- θ_{23} octant
- CP violation

ν_μ disappearance

- Improved precision on $|\Delta m^2_{32}|$ and θ_{23}

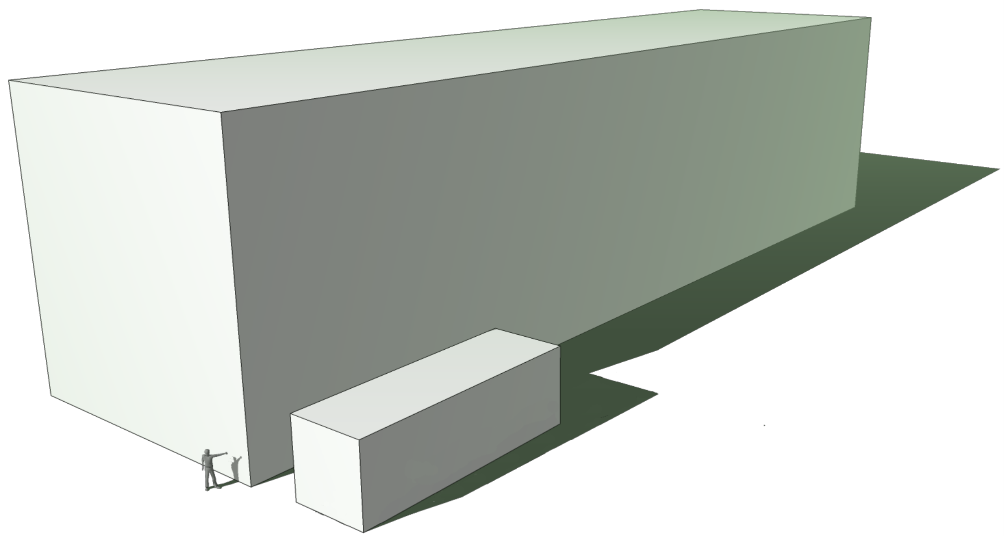
NC disappearance

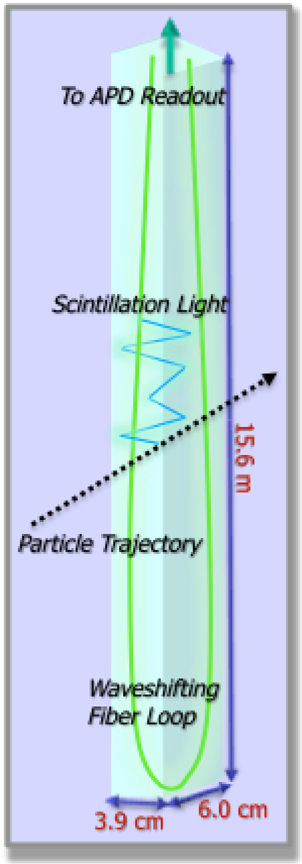
- Search for sterile neutrinos
- Constrain θ_{34} and θ_{24}

Others

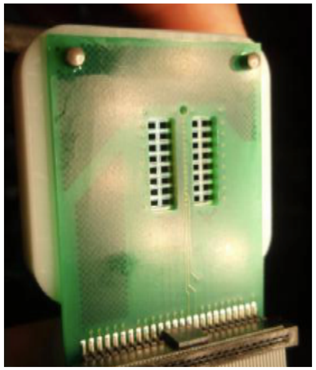
- Short-baseline steriles
- Cross sections
- Supernovae
- Exotics

NOvA Detector Design





Low Z tracking calorimeter composed of alternating horizontal and vertical planes of liquid scintillator filled cells.



Wavelength shifting fibers carry light out of the cells to APDs.

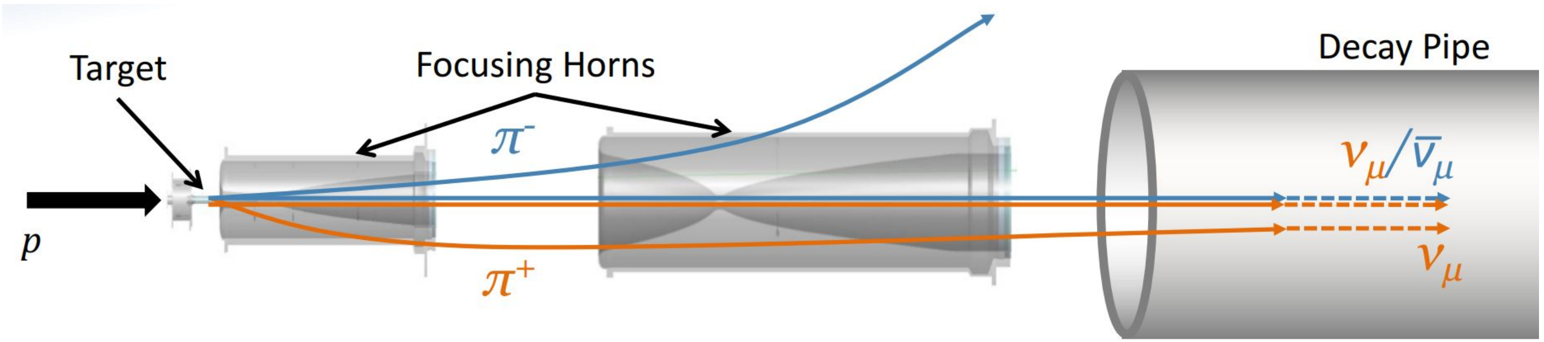
Far detector (FD)

- 14 kton
- 15m x 15m x 60m
- 65% active mass
- ~344,000 channels

Near detector (ND)

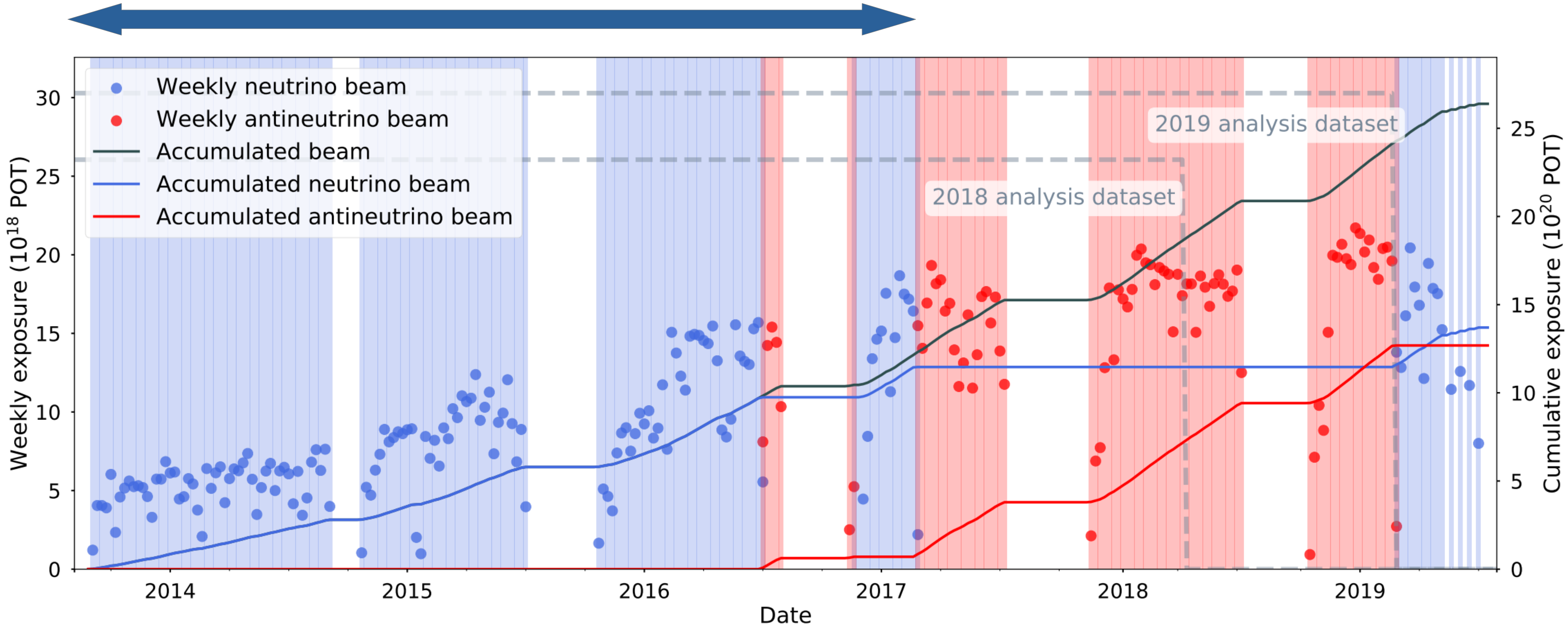
- 0.3 kton
- 3.8m x 3.8m x 12.8m (main detector)
- Functionally equivalent to FD for systematic uncertainty reduction
- ~20,000 channels

NuMI Neutrino Beam

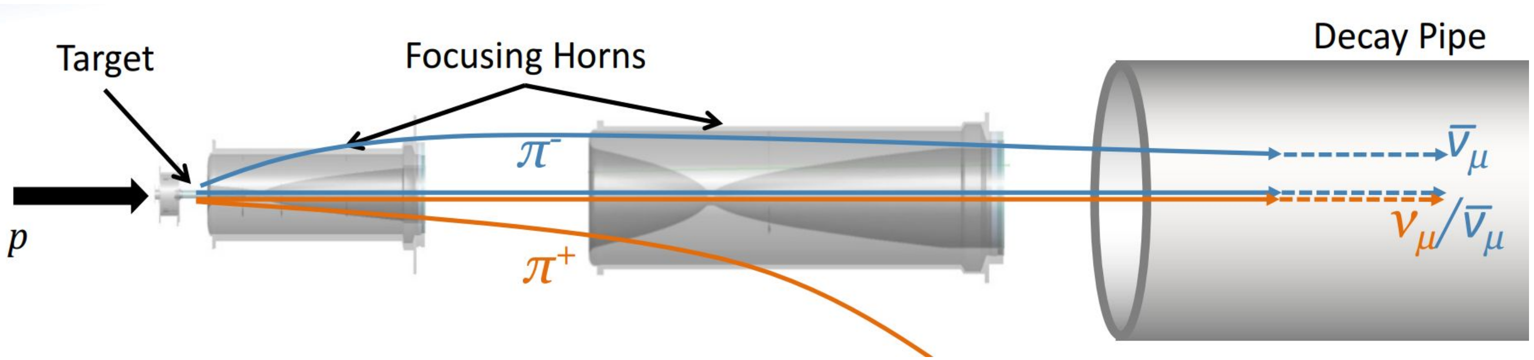


NuMI is the world's most powerful neutrino beam → running at 700 kW power since January 2017

Recorded 8.85 x 10^{20} protons on target (POT) in neutrino mode

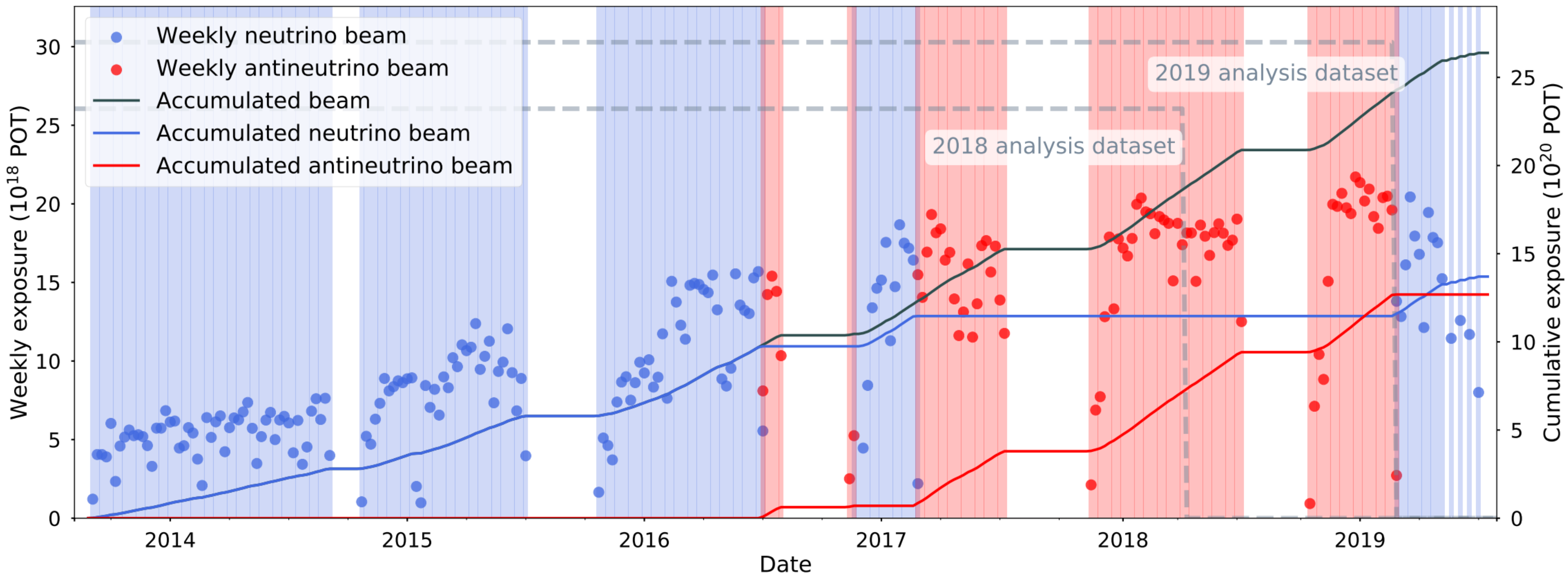


NuMI Antineutrino Beam

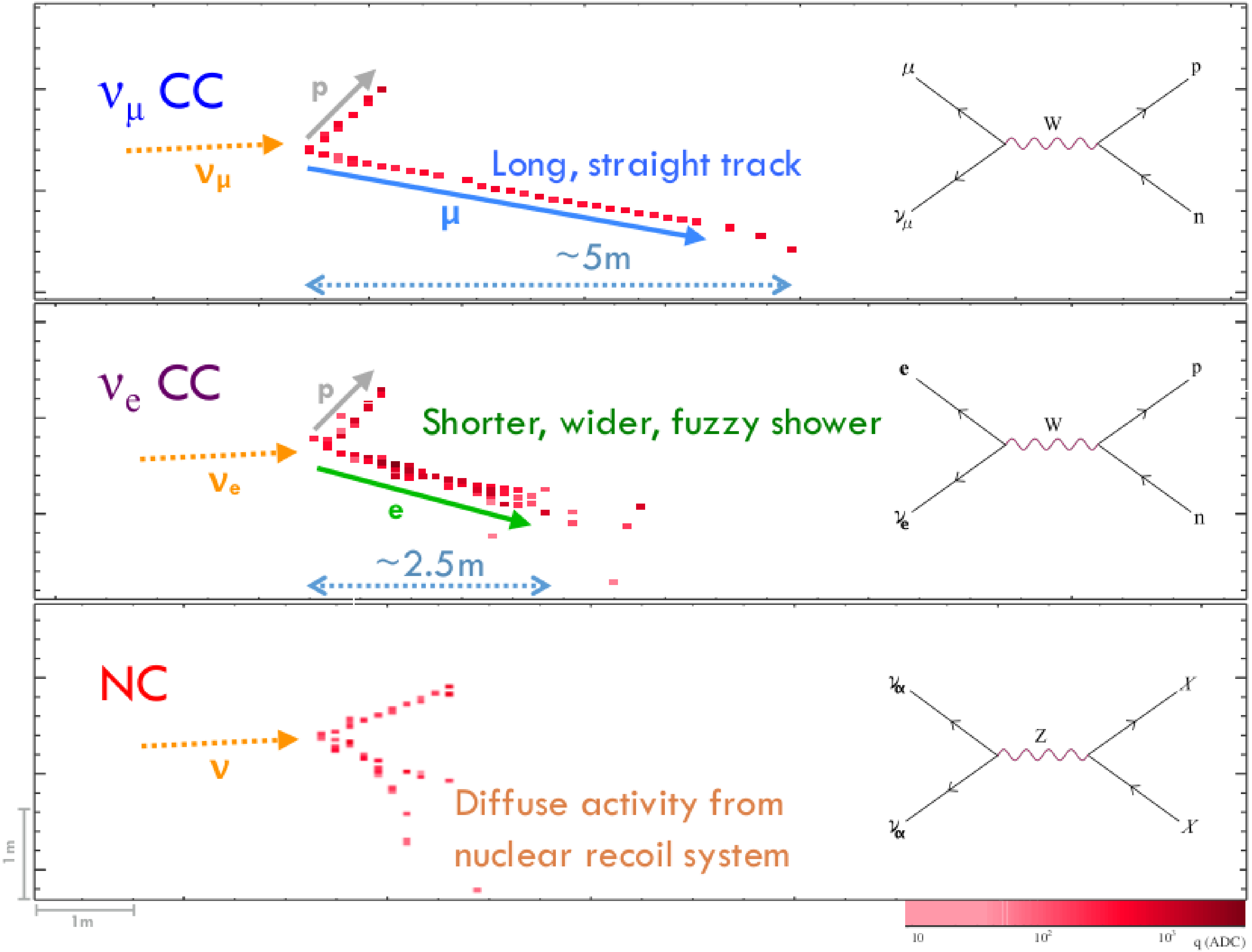


NuMI is the world's most powerful neutrino beam → running at 700 kW power since January 2017

Recorded 12.5 x 10^{20} protons on target (POT) in antineutrino mode



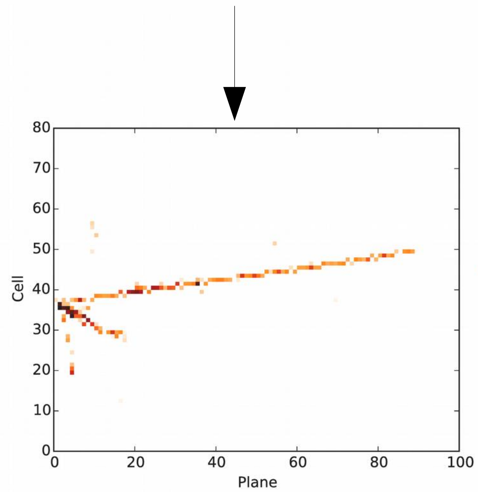
Event Topologies



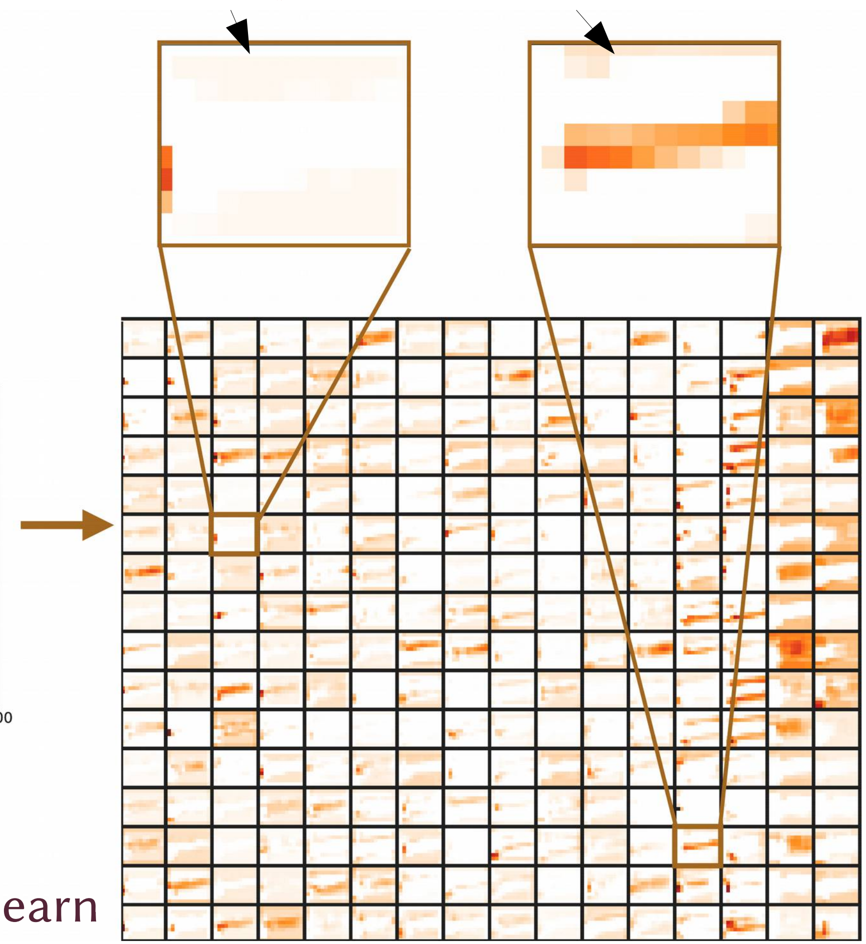
Neutrino Interaction Classifier

- Convolutional Visual Network (CVN) is a selection algorithm based on Deep-Learning techniques
- Uses all information in minimally reconstructed events
- Is a multi-purpose classifier
  - Capable of selecting ν_e, ν_μ, ν_τ, NC, and cosmics

Treat each event as an image with cells as pixels and charge as color value



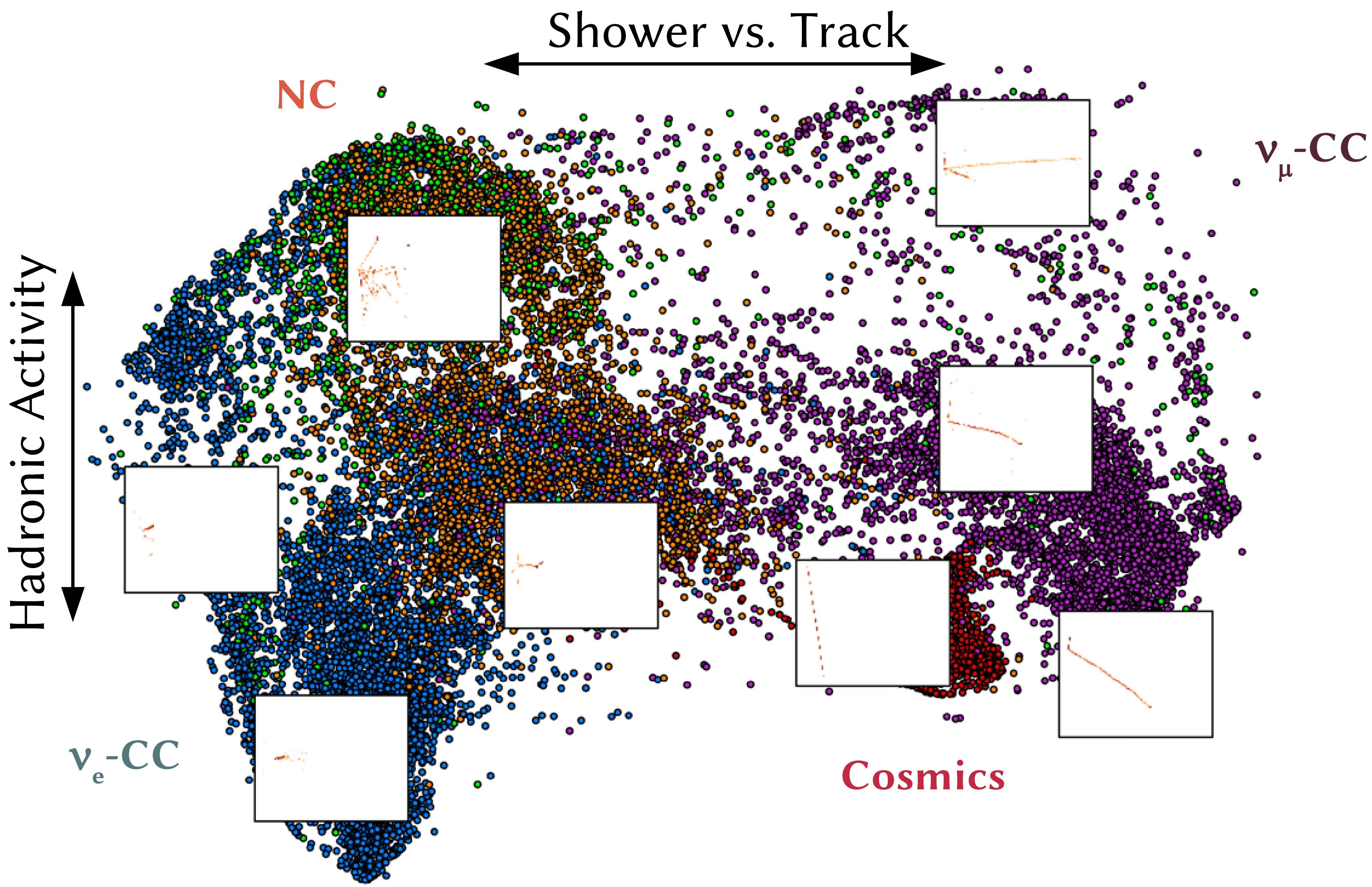
Individual learned filters are sensitive to physics: e.g. hadronic activity or muon tracks



Convolutional layers learn filters to optimally extract features from the data

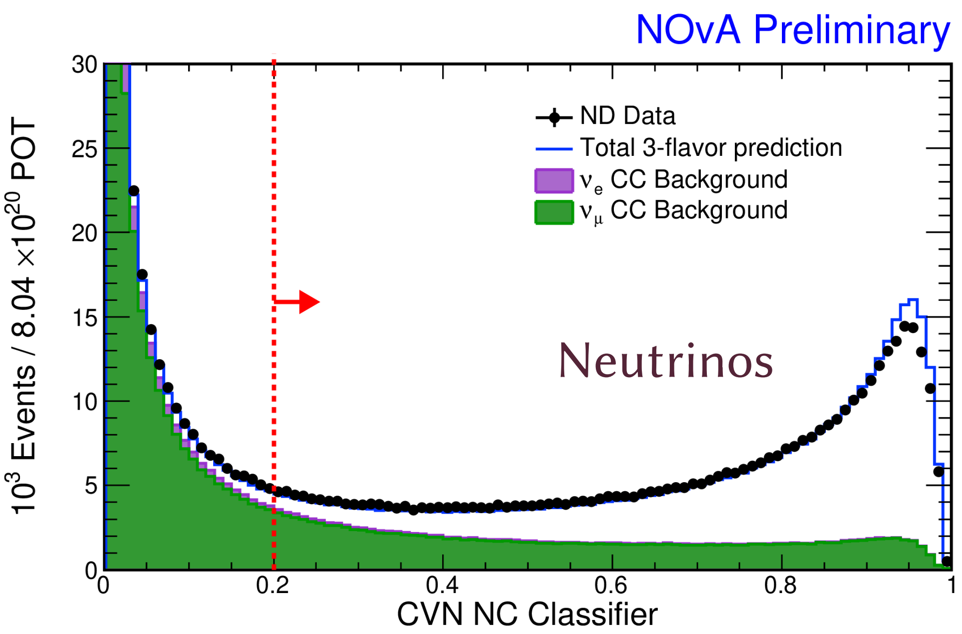
JINST 11 (2016) P09001

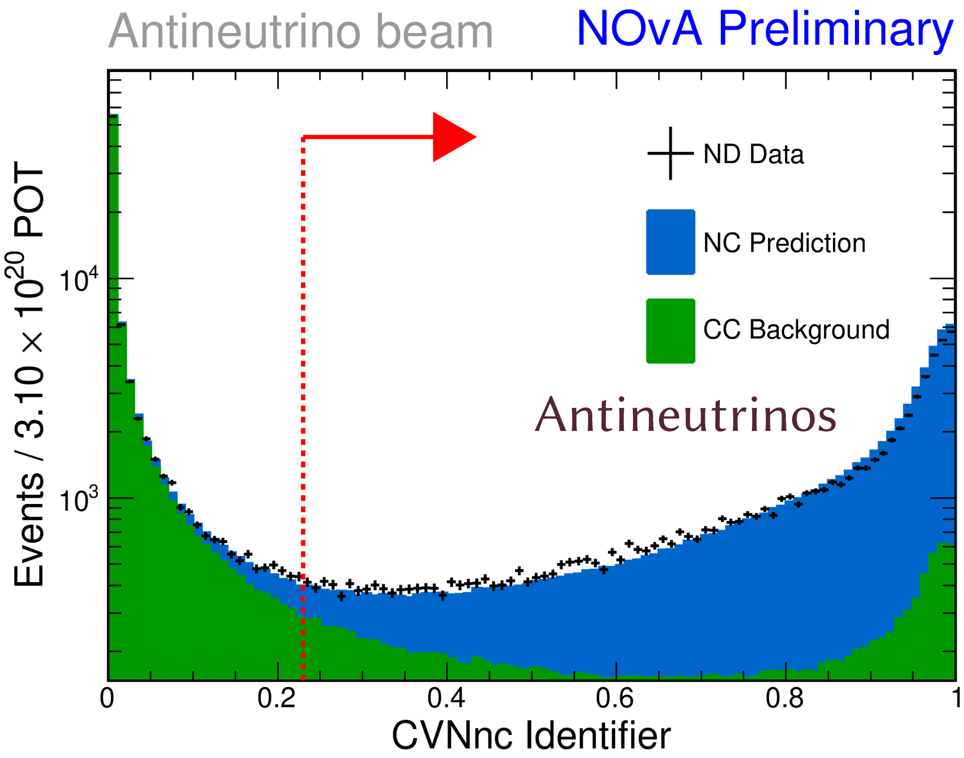
Neutrino Interaction Classifier



- All current oscillation analyses use this ID with different optimizations
- Trained for the neutrino and antineutrino beams separately
- Cosmic data is included in training

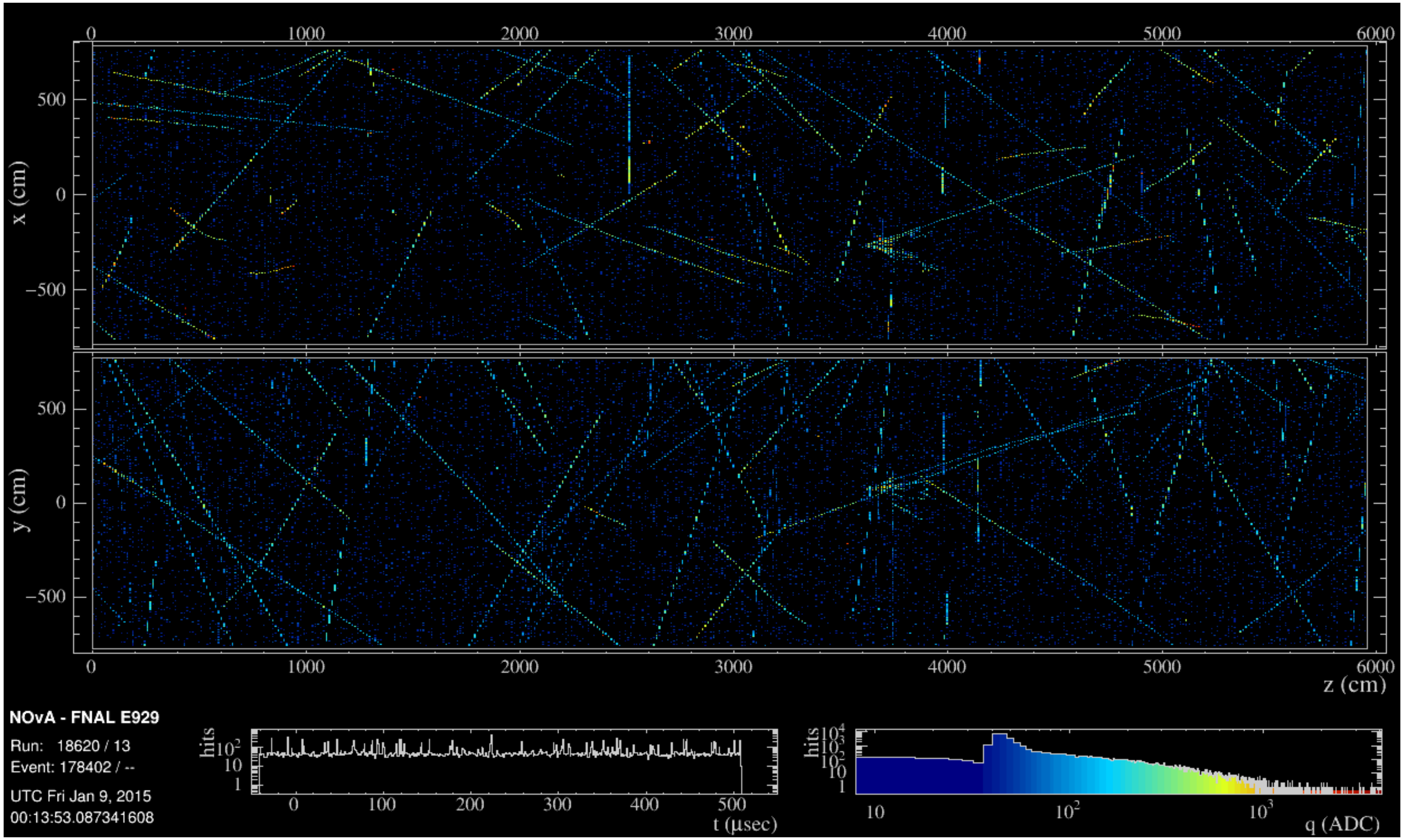
Near Detector CC/NC Separation





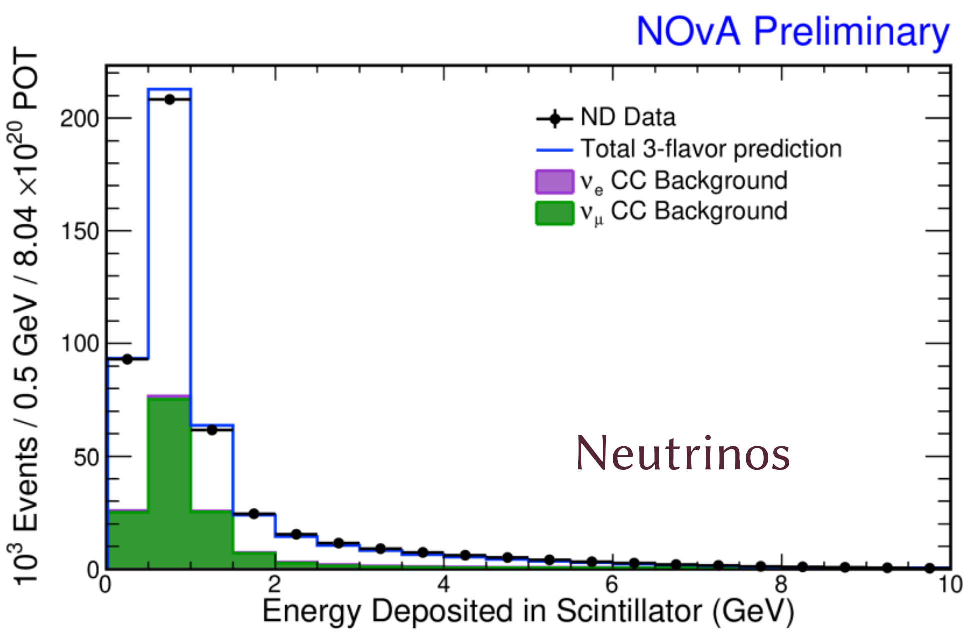
- CVN provides excellent CC/NC separation
- Good data/MC agreement within systematic uncertainties

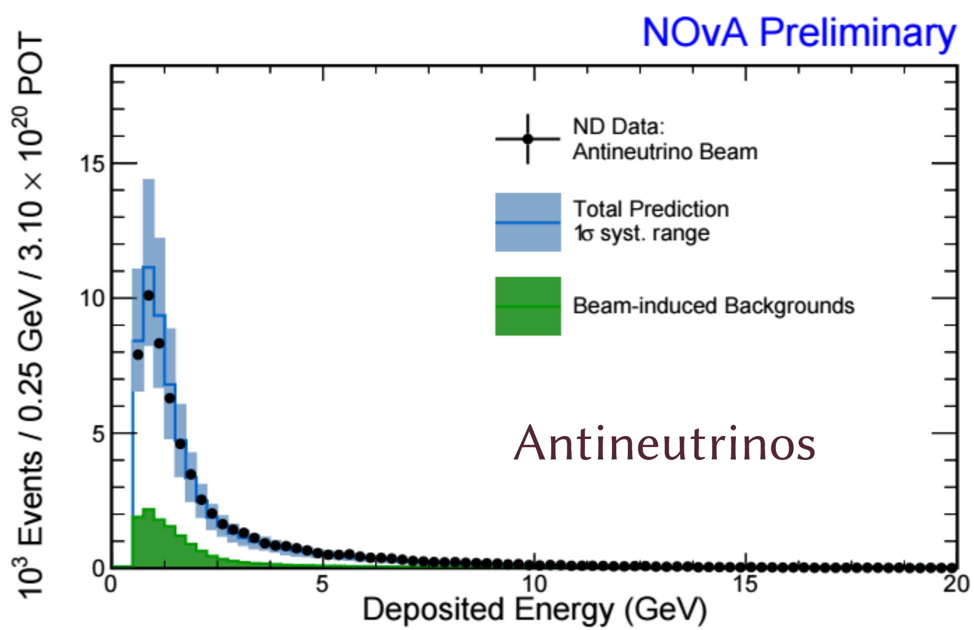
Rejecting Cosmic Events



- The FD sees ~150,000 cosmic rays/second
- CVN removes most cosmic rays with muons, but cosmogenic neutrons can be difficult to separate from NC events
- Use a BDT designed to separate cosmogenic neutrons and NC events using reconstructed shower variables

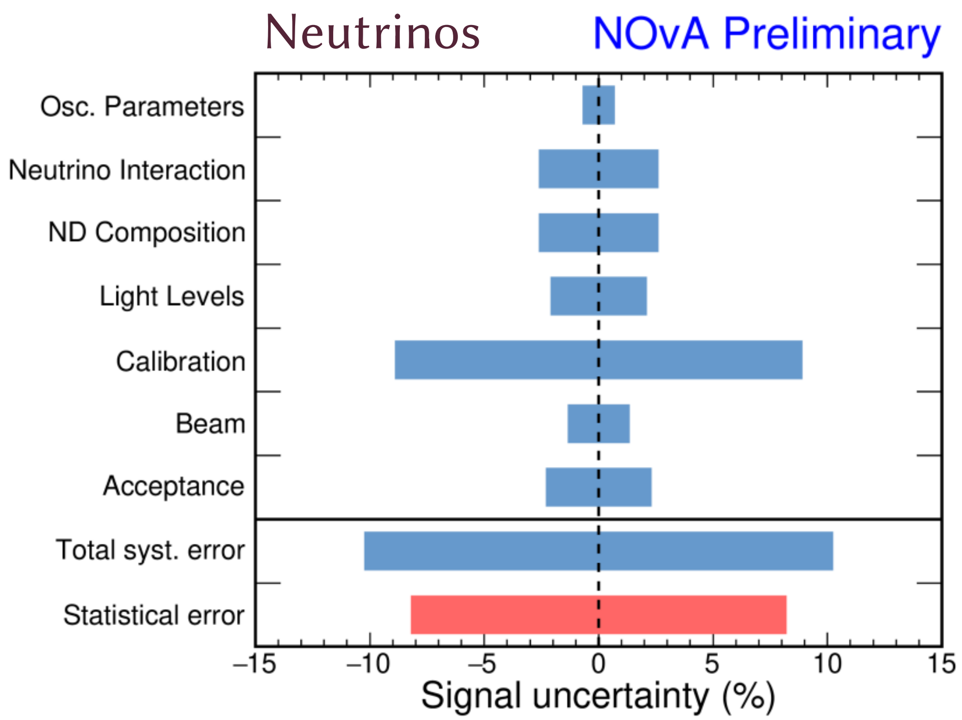
Near Detector Spectra

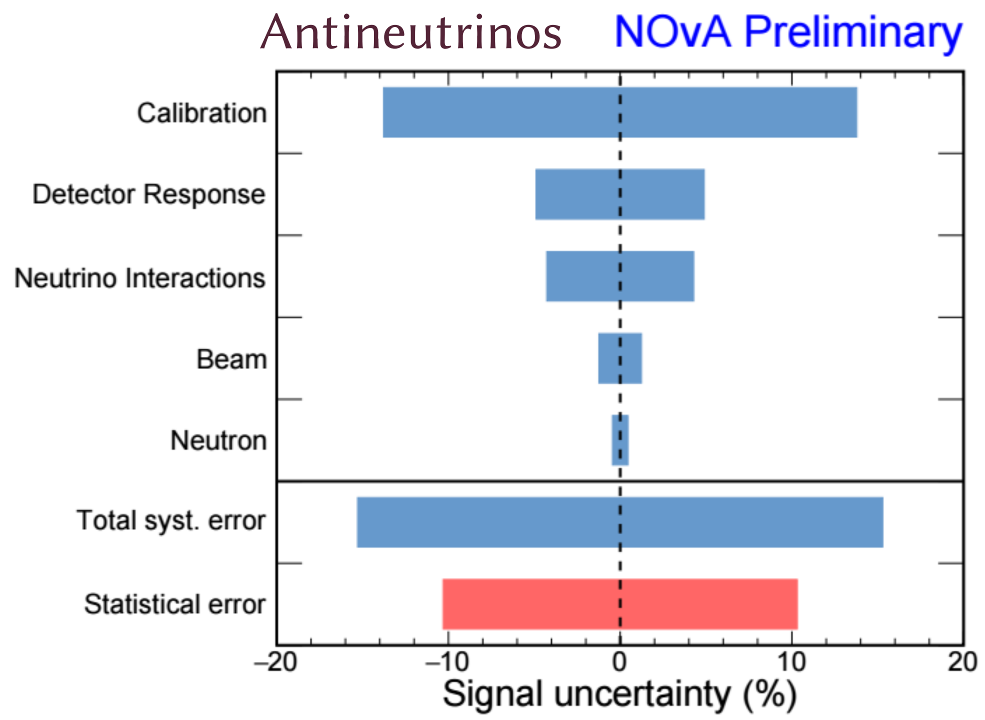




- CVN selector excellent at separating NC signal from beam backgrounds
- Good data/MC agreement in the ND in both the neutrino and antineutrino beams
- Assuming no oscillations at the ND, its data can be used to predict the event rate at the Far Detector
- This partially cancels systematic uncertainties correlated between the detectors

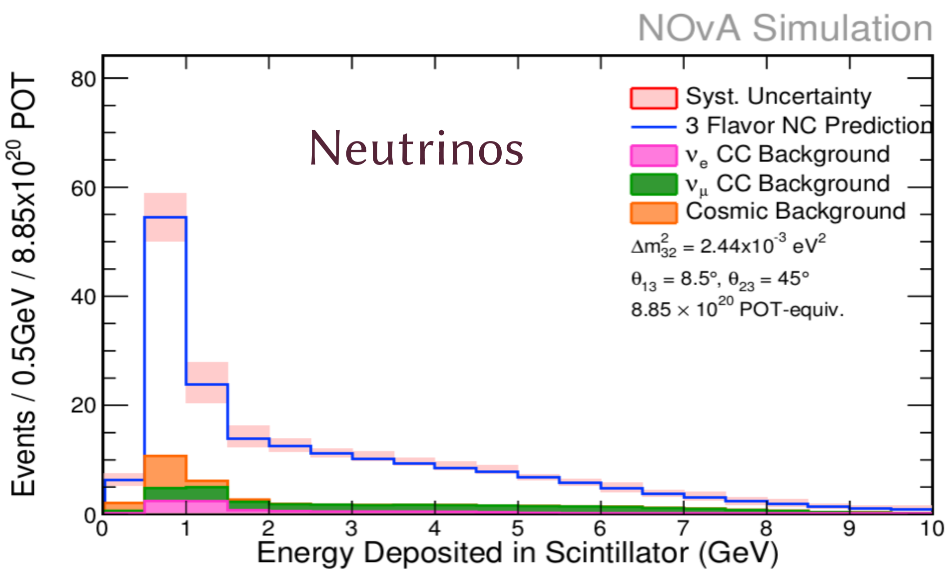
NC Systematics

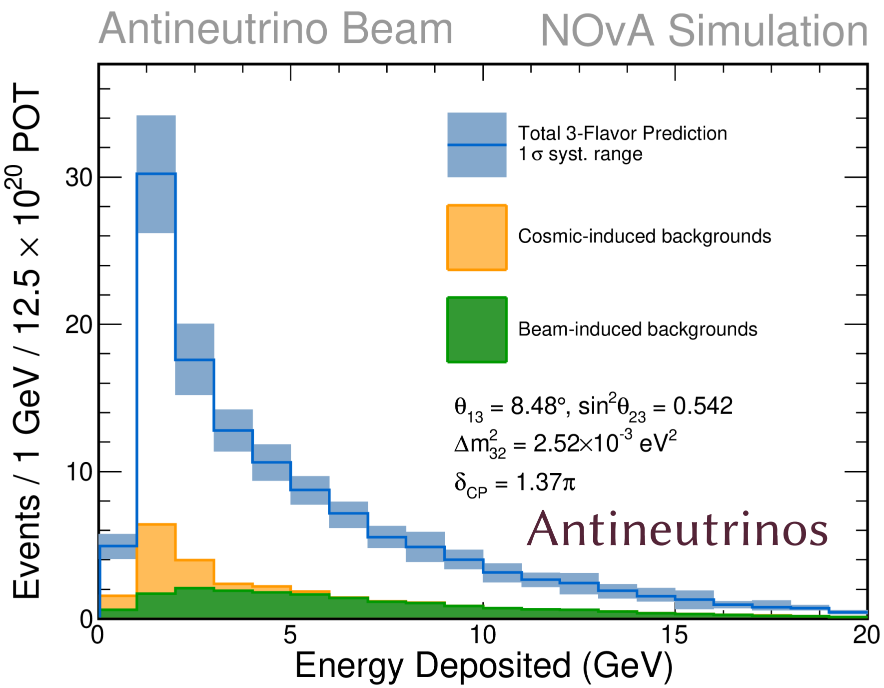




- NC events consist of an out-going neutrino and a hadronic recoil system
- Visible energy deposited is measured calorimetrically, resulting in a large calibration systematic uncertainty
- Measuring the absolute detector response for pions in the upcoming test beam program will significantly improve this uncertainty

FD Prediction

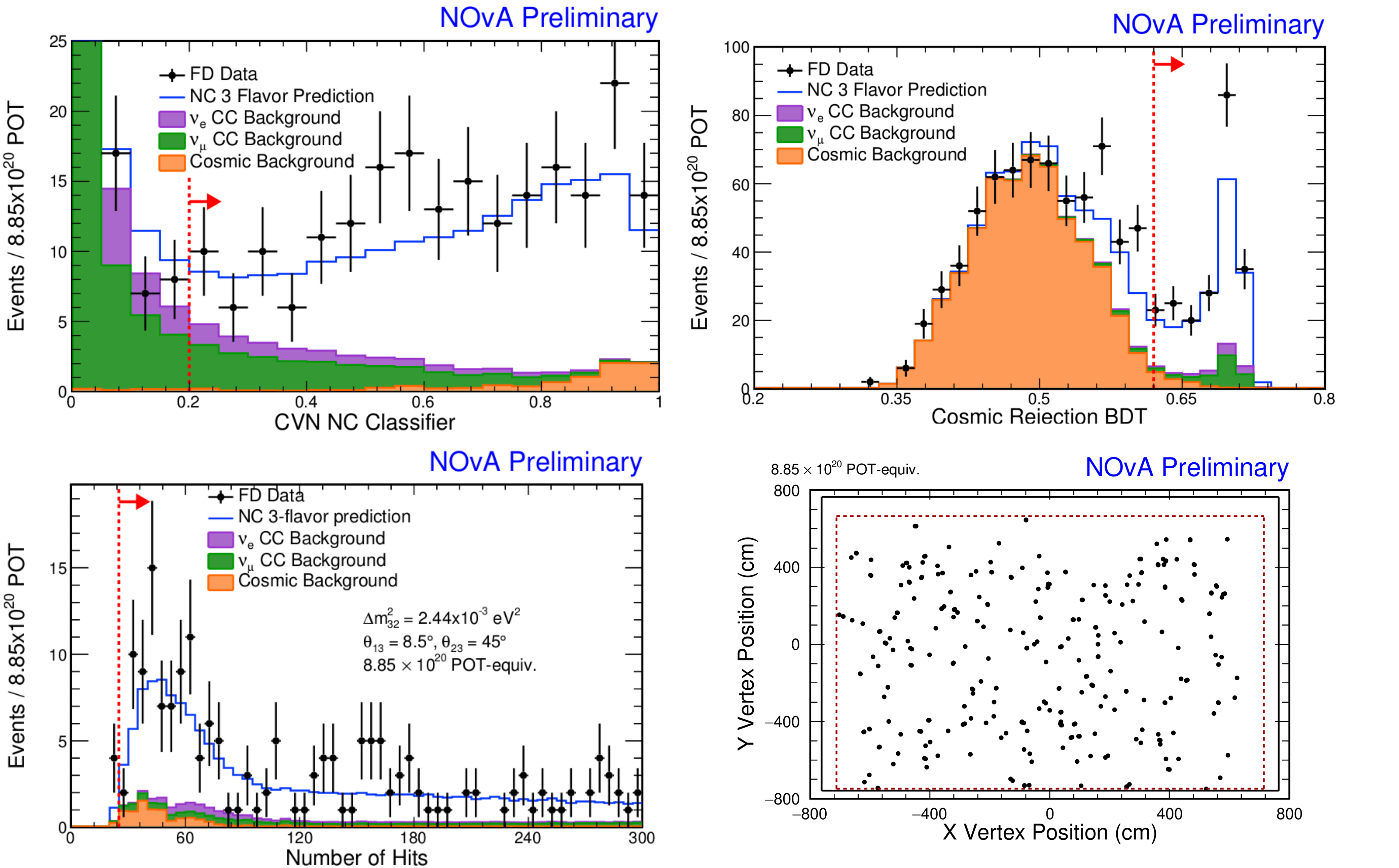




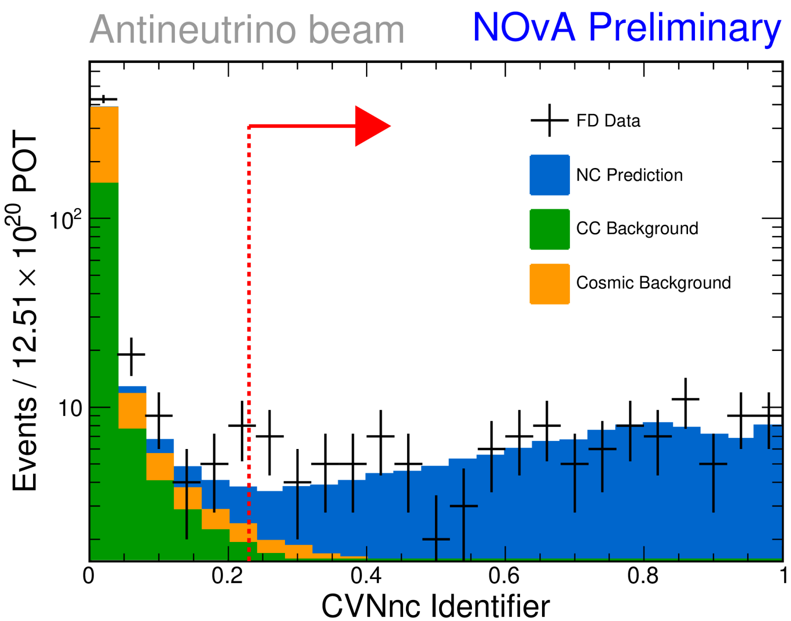
- Prediction: 191 total
  - 148 NC signal
  - 36 CC background
  - 8 cosmic rays
- 52% efficiency, 77% purity

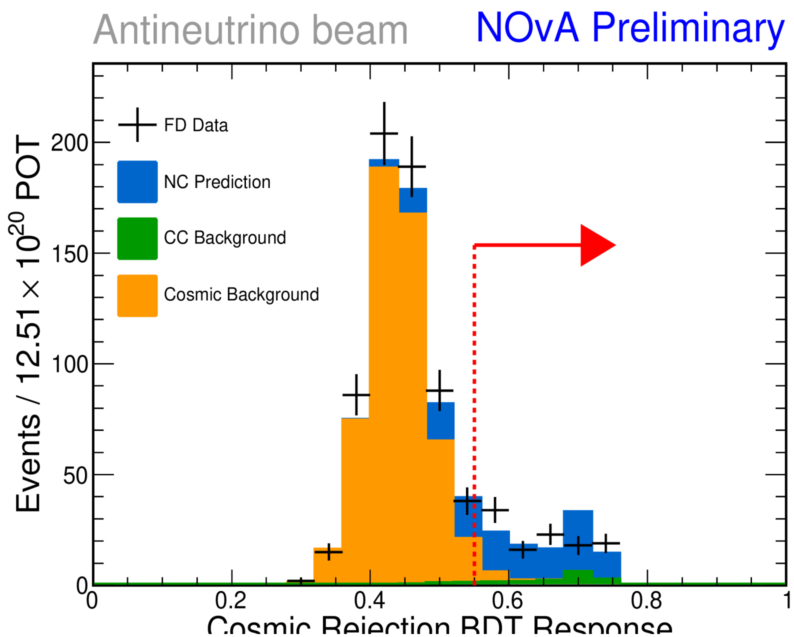
- Prediction: 122 total
  - 95 NC signal
  - 18 CC background
  - 9 cosmic rays
- 50% efficiency, 77% purity

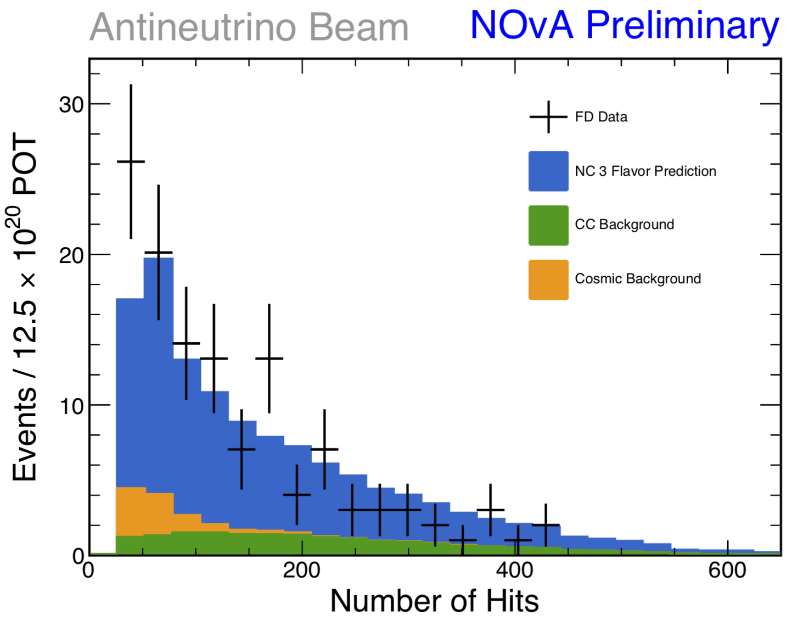
Far Detector Distributions - Neutrinos

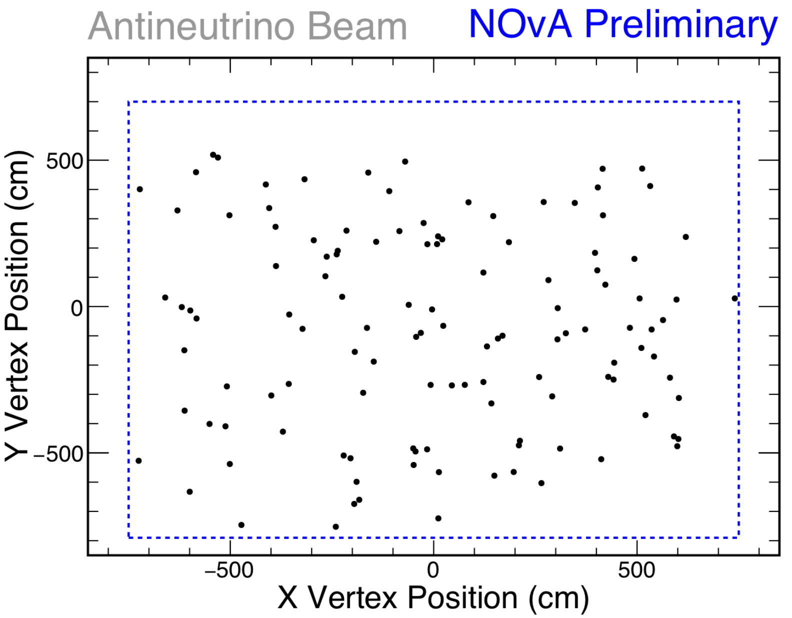


Far Detector Distributions - Antineutrinos

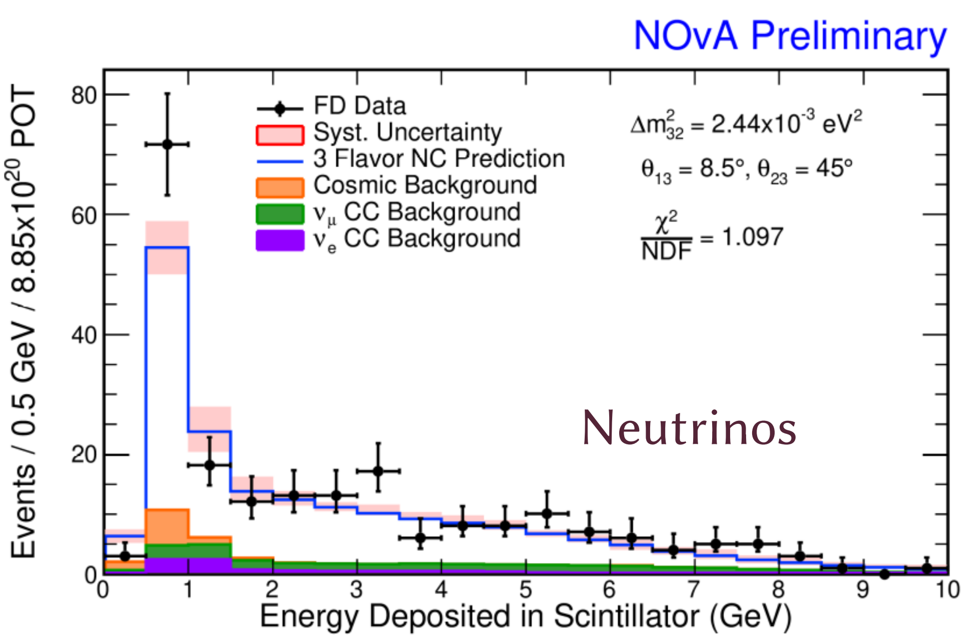


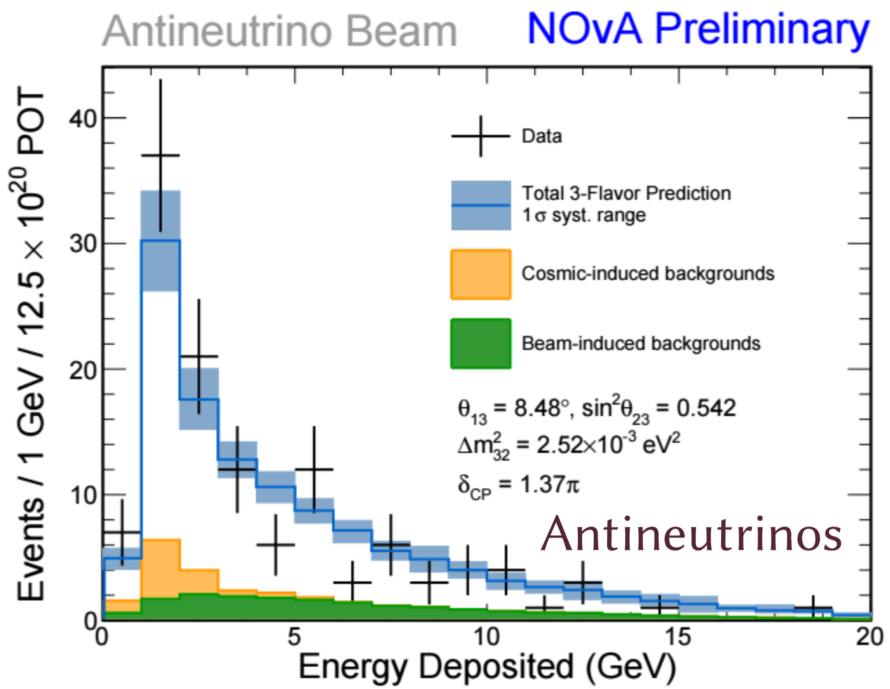






Far Detector Spectra

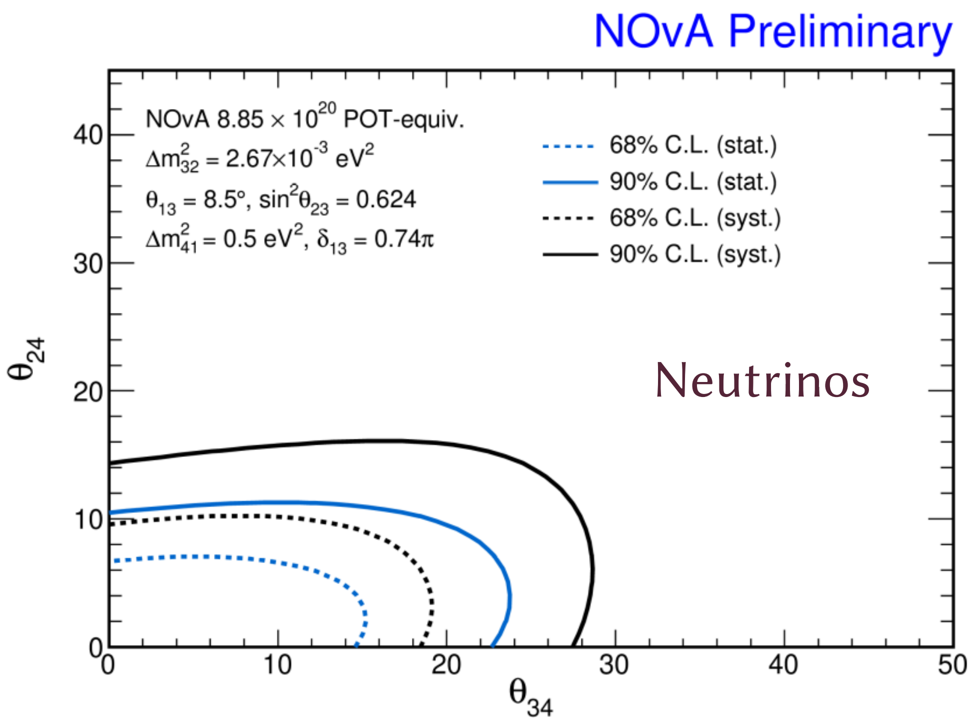


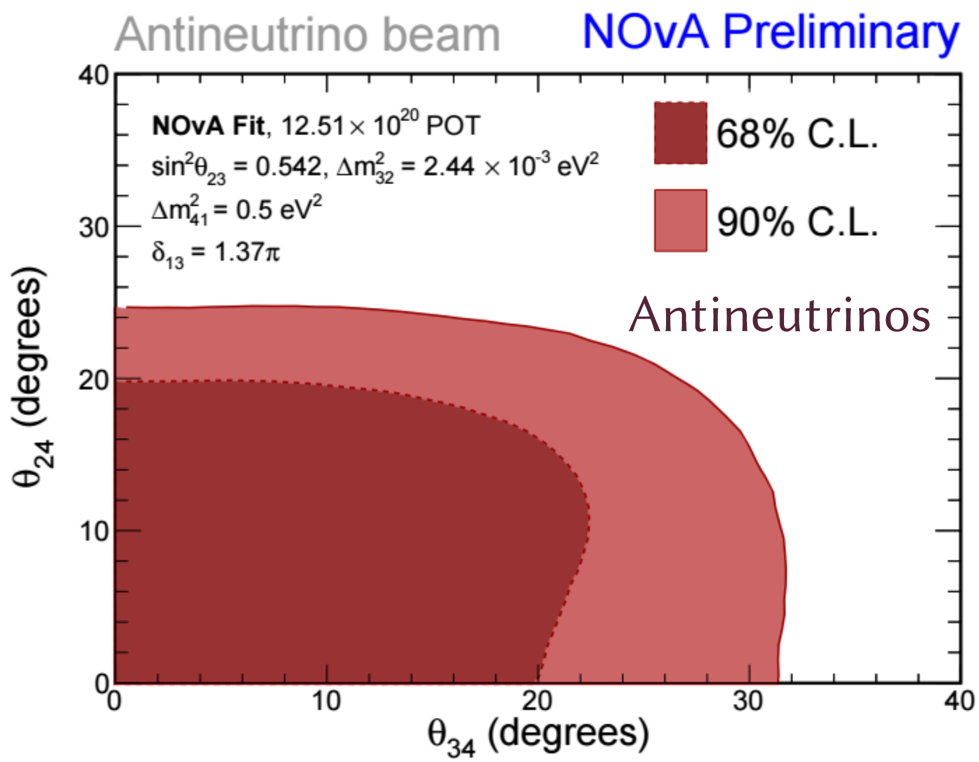


- Neutrino data:
  - Predicted **191.2 ± 13.8 (stat)** ± **22.0** (syst) events
  - Observed **214** events
- Antineutrino data:
  - Predicted **122 ± 11 (stat) ± 18 (syst)** events
  - Observed **121** events

No significant suppression of neutral current interactions for neutrinos or antineutrinos observed

Neutrino and Antineutrino Limits





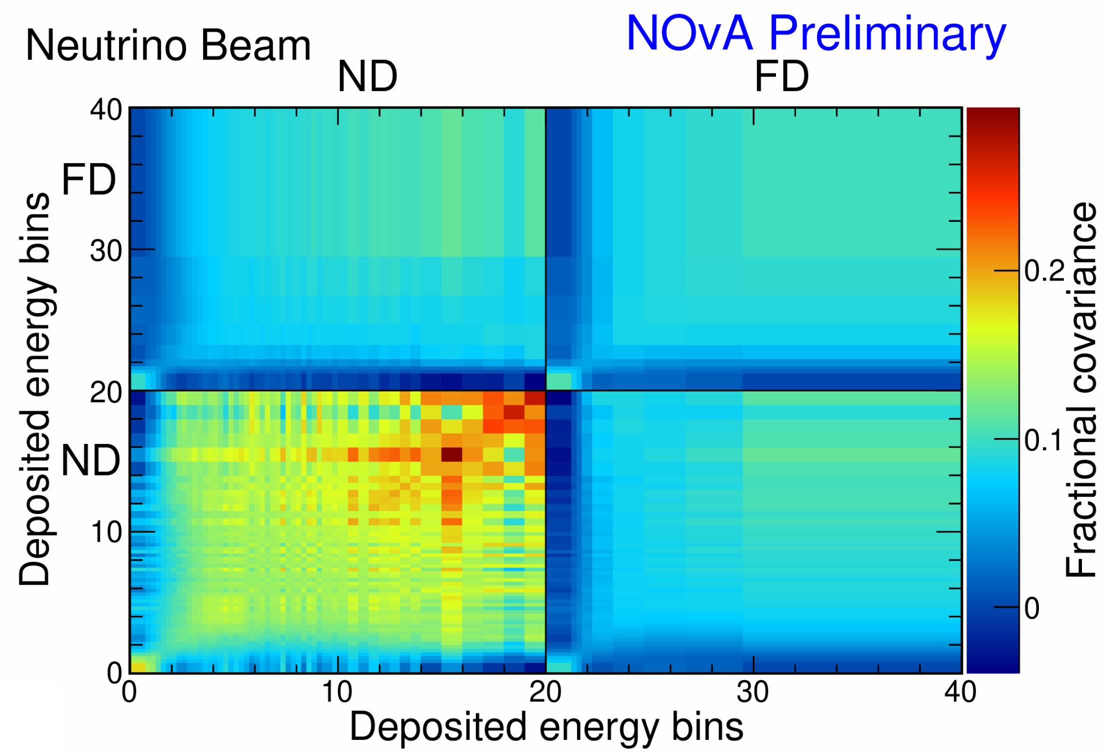
1D 90% C.L. limits

	θ_{24}	θ_{34}	$\|U_{\mu4}\|^2$	$\|U_{\tau4}\|^2$
NOvA 2019 ($\bar{\nu}$)	24.7°	31.7°	0.175	0.276
NOvA 2017 (ν)	16.2°	29.8°	0.078	0.247
NOvA 2016 (ν)	20.8°	31.2°	0.126	0.268
MINOS/MINOS+	4.4°	23.6°	0.006	0.160
SuperK	11.7°	25.1°	0.041	0.180
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.150

The Future

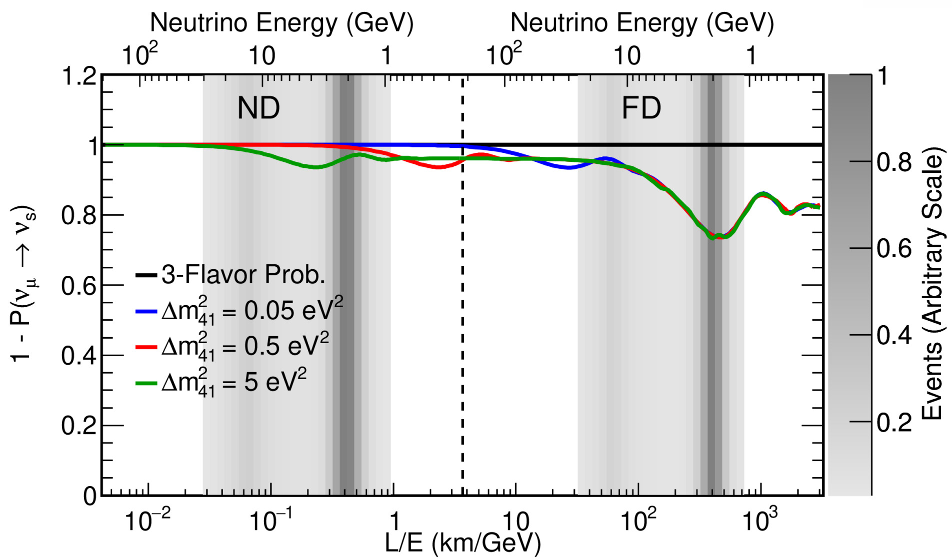
Two Detector Fit

- At high Δm^2_{41}, extrapolation method breaks down due to disappearance in Near Detector.
- Perform joint fit in both detectors, treating ND and FD on equal footing
- Use covariance matrix to account for correlated systematics between two detectors, maintaining the cancellation of uncertainties
  - Technique recently used by MINOS/MINOS+ (Phys. Rev. Lett. 122, 091803 (2019)), but this will be the first use in NOvA



$$V_{ij,\mathrm{syst}} = \frac{\sum_{n=1}^{U} (S_{n,i} - \mu_i)(S_{n,j} - \mu_j)}{U - 1}$$

$$\chi^2 = \sum_{i=1}^{N} \sum_{j=1}^{N} (x_i - \mu_i)[V^{-1}]_{ij}(x_j - \mu_j)$$



Test Beam

- The test beam detector will be exposed to a tertiary beam of e, p, $\pi^{\pm}$, and K with known momentum in the range 0.2 – 2.0 GeV/c.
- Will provide absolute measurement of detector response and a cross-check on the calibration chain
- Critical for future analysis improvements
  - Reduced systematics (calibration and hadronic modeling)
  - Validation of machine learning techniques
  - Validation of simulation improvements
- Installation started in summer 2018, commissioning run in spring 2019
- Beam operations starting after summer shutdown, planning on 2 million particles

Summary

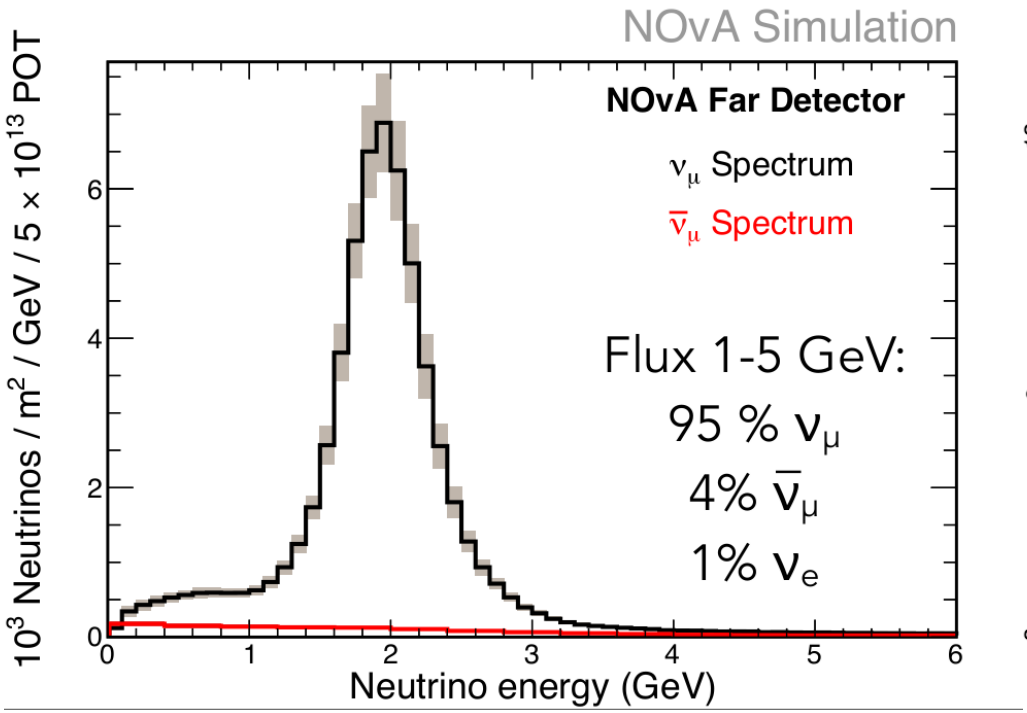
- Performed a search for depletion in the NC rate at the NOvA FD with 8.85×10^{20} POT in neutrino mode and 12.5×10^{20} POT in antineutrino mode
- Observe no evidence for sterile-neutrino-driven oscillations in the neutral current channel in either neutrino or antineutrino beam modes
  - Neutrino mode, 90% CL
    - $\theta_{24} < 16.2°$, $\theta_{34} < 29.8°$
  - Antineutrino mode, 90% CL
    - $\theta_{24} < 24.7$, $\theta_{34} < 31.7°$
  - Results are competitive with other experiments with 1/3 of planned exposure
- Analysis improvements to allow for fitting a wider range of Δm^2_{41} are in progress
- Test beam program is in progress to significantly reduce uncertainties on detector response to hadrons, currently the dominant uncertainty
- Stay tuned!

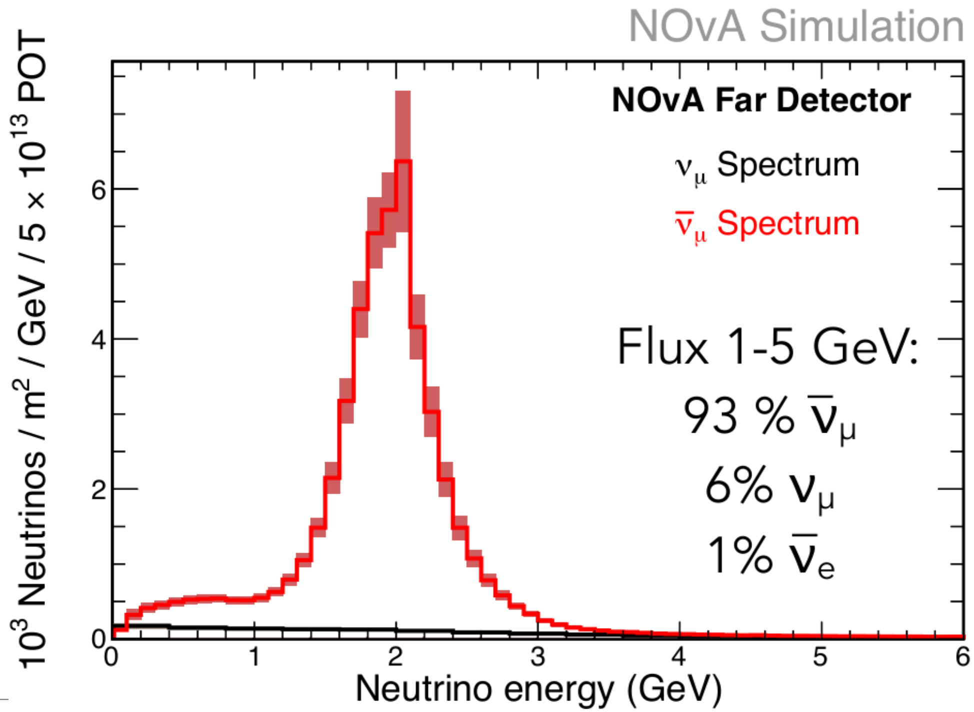
Thank You!

http://novaexperiment.fnal.gov

Backup Slides

Off-axis Flux



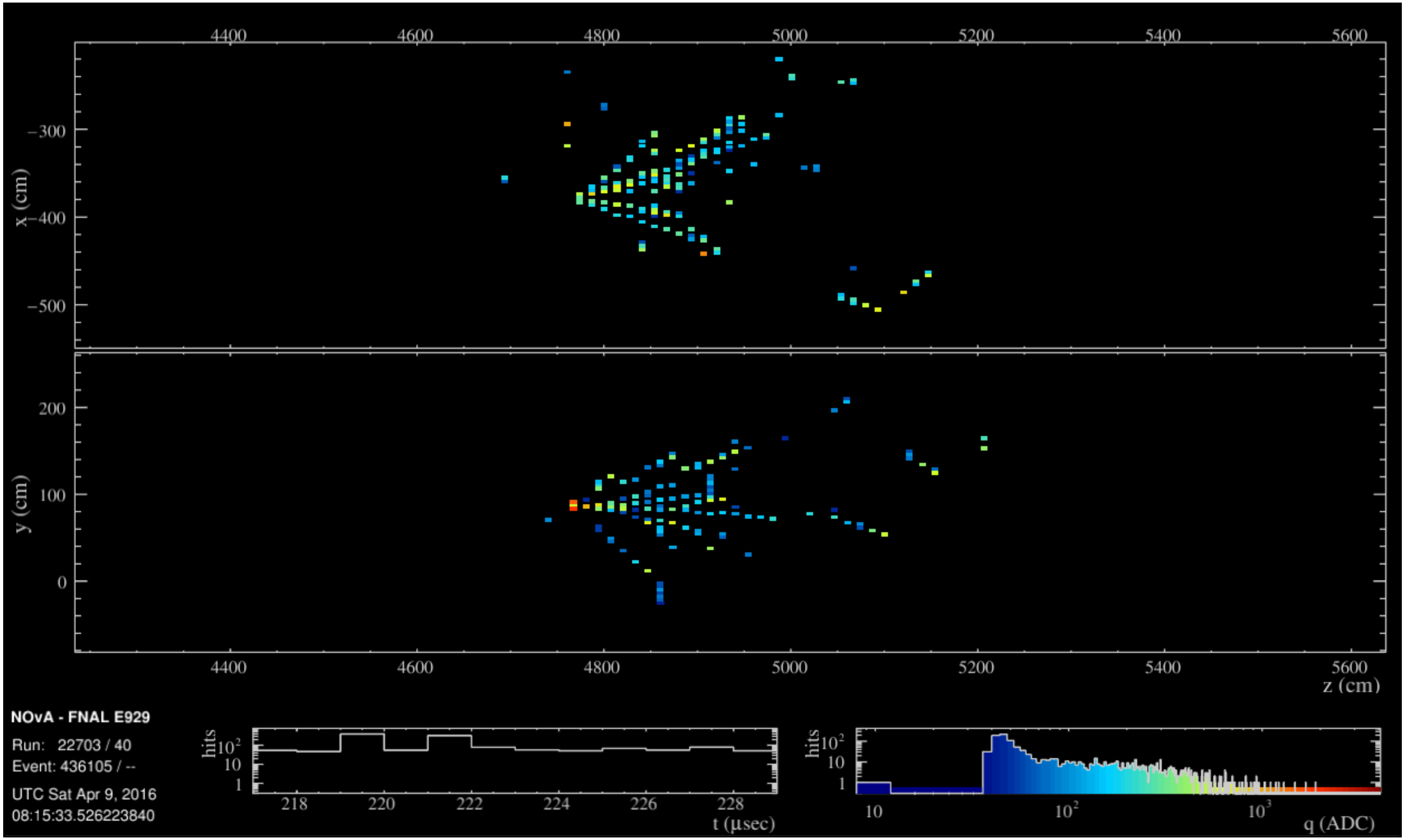


- Off-axis at 14 mrad, peaks just above the oscillation maximum. Small wrong-sign component for both configurations
- Flux prediction of the NuMI beam at the NOvA detectors made using the Package to Predict the Flux (PPFX), a method developed by MINERvA (Phys. Rev. D 94 (2006) 092005)
- Beam optics uncertainties are incorporated by propagating errors in the alignment of beam-line elements

FD Efficiencies and Purities

	Efficiency	Purity
$\nu_\mu - CC$	31.2%	98.6%
$\bar{\nu}_\mu - CC$	33.9%	98.8%
$\nu_e - CC$	62%	57%-78%
$\bar{\nu}_e - CC$	67%	55%-77%
$\nu_x - NC$	52%	77%
$\bar{\nu}_x - NC$	50%	77%

NC Candidate Event



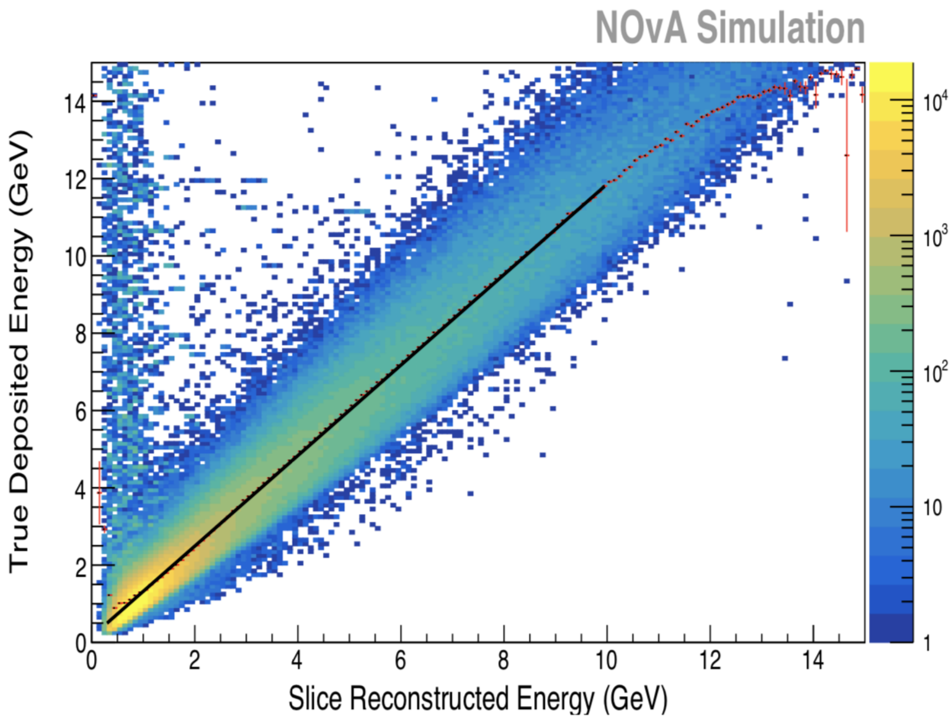
1D 90% World Limit References

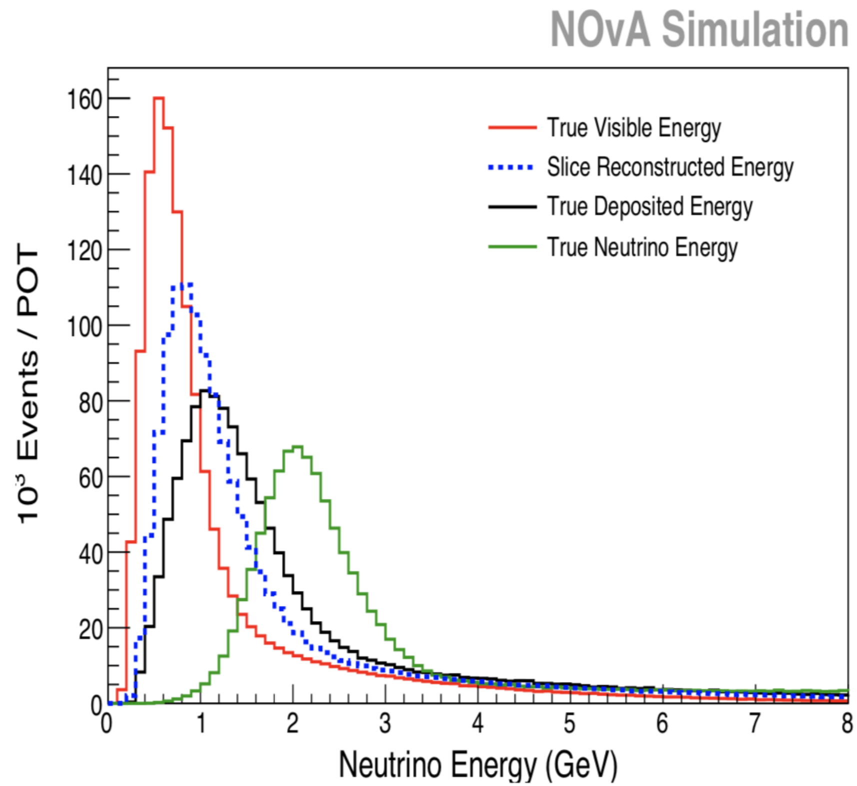
- NOvA 2017: unpublished, e.g. DPF 2017 proceedings ()
- NOvA 2016: Phys. Rev. D **96**, 072006 (2017)
- MINOS/MINOS+: Phys. Rev. Lett. **122**, 091803 (2019)
- SuperK: Phys. Rev. D **91**, 052019 (2015)
- IceCube: Phys. Rev. Lett. **117**, 071801 (2016)
- IceCube-DeepCore: Phys. Rev. D **95**, 112002 (2017)

Antineutrino Goodness of Fit

- $\chi 2$/DOF = 79 / 76 = 1.04.

Energy Reconstruction





- Determine 'calorimetric energy' based on calibrated charge collected in detector.
- Use simulation to convert reconstructed energy into 'true deposited energy' in the event.
- Final energy resolution ~25%.