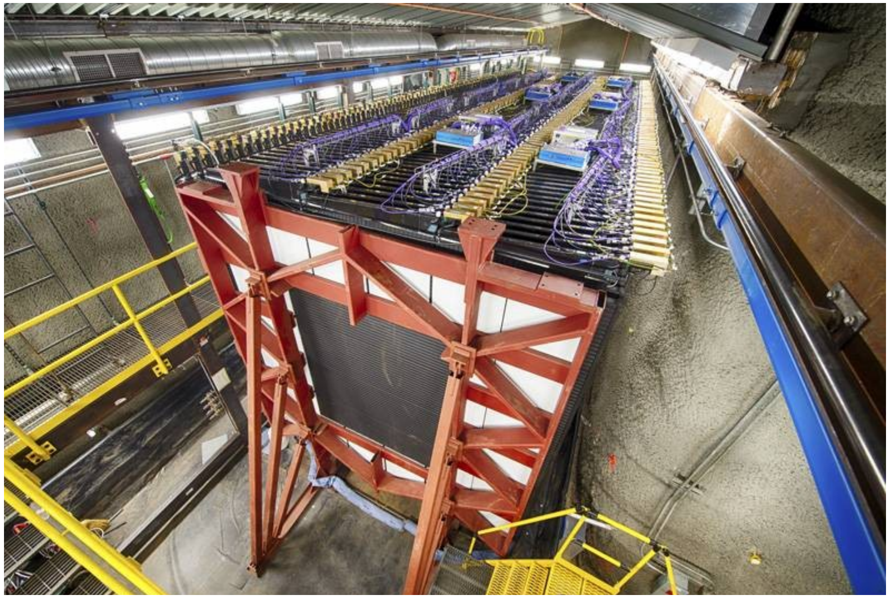
Recent Results from NOvA

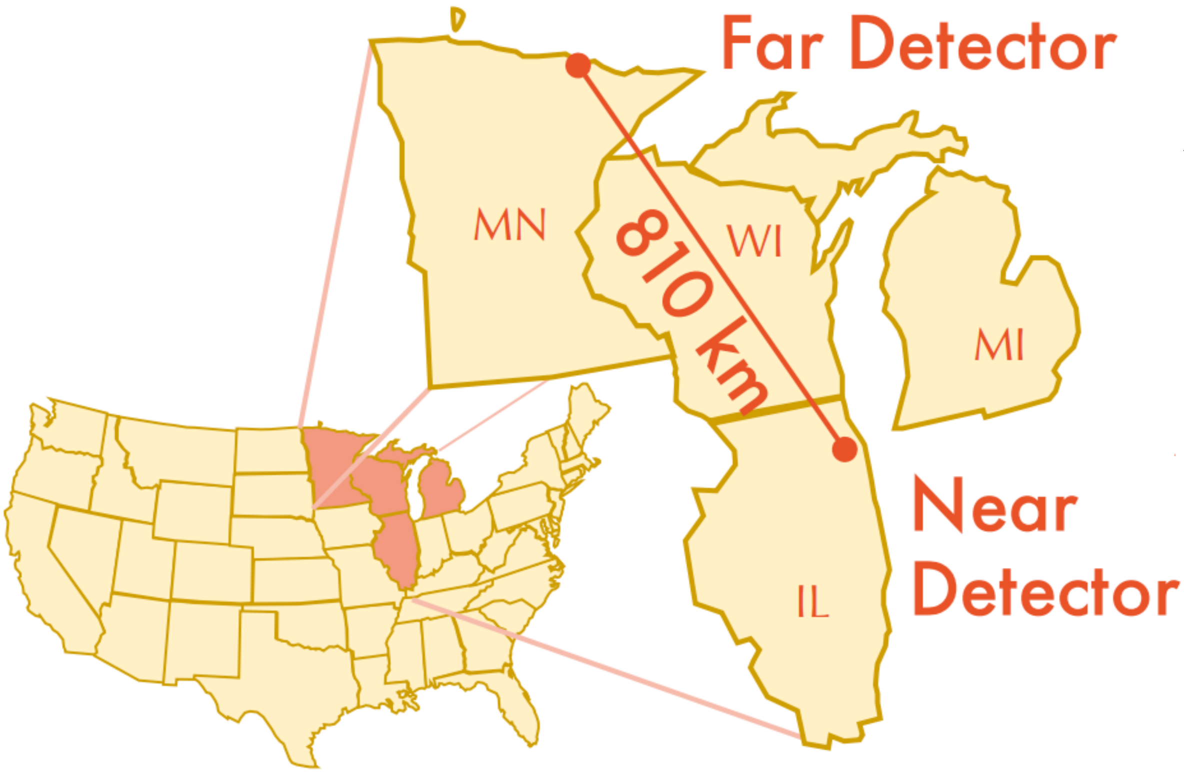


Adam Aurisano
University of Cincinnati

XVIII International Workshop on Neutrino Telescopes
19 March 2019

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

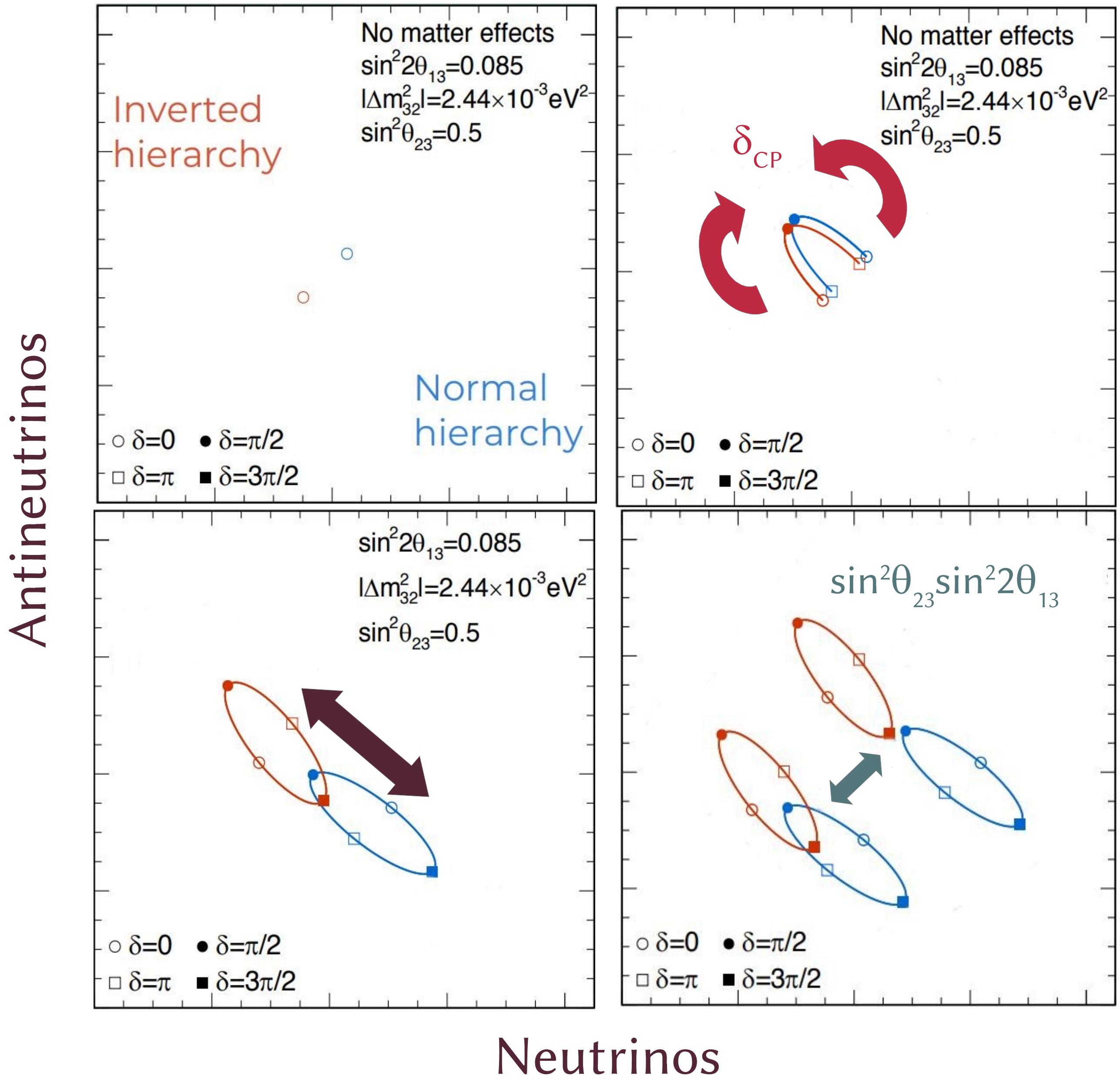
- Search for sterile neutrinos
- Constrain θ_{34} and θ_{24}

Others

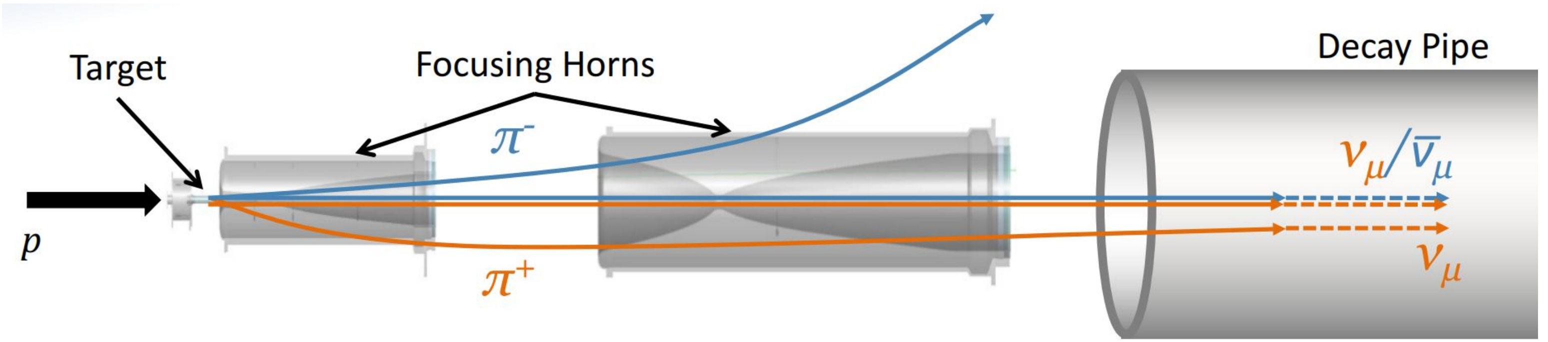
- Short-baseline steriles
- Cross sections
- Supernovae
- Exotics

Need for Both Neutrinos and Antineutrinos

- The primary change between the analysis shown here and our previous analysis (Phys. Rev. D 98 (2018) 032012) is the addition of antineutrino data.
- Critical to measure both neutrinos and antineutrinos:
  - IH ⟶ slight suppression compared to NH
  - CP violation causes opposite effects in neutrinos and antineutrinos
  - Matter effects also produce opposite effects in neutrinos and antineutrinos
  - The octant of θ_{23} affects neutrinos and antineutrinos the same way

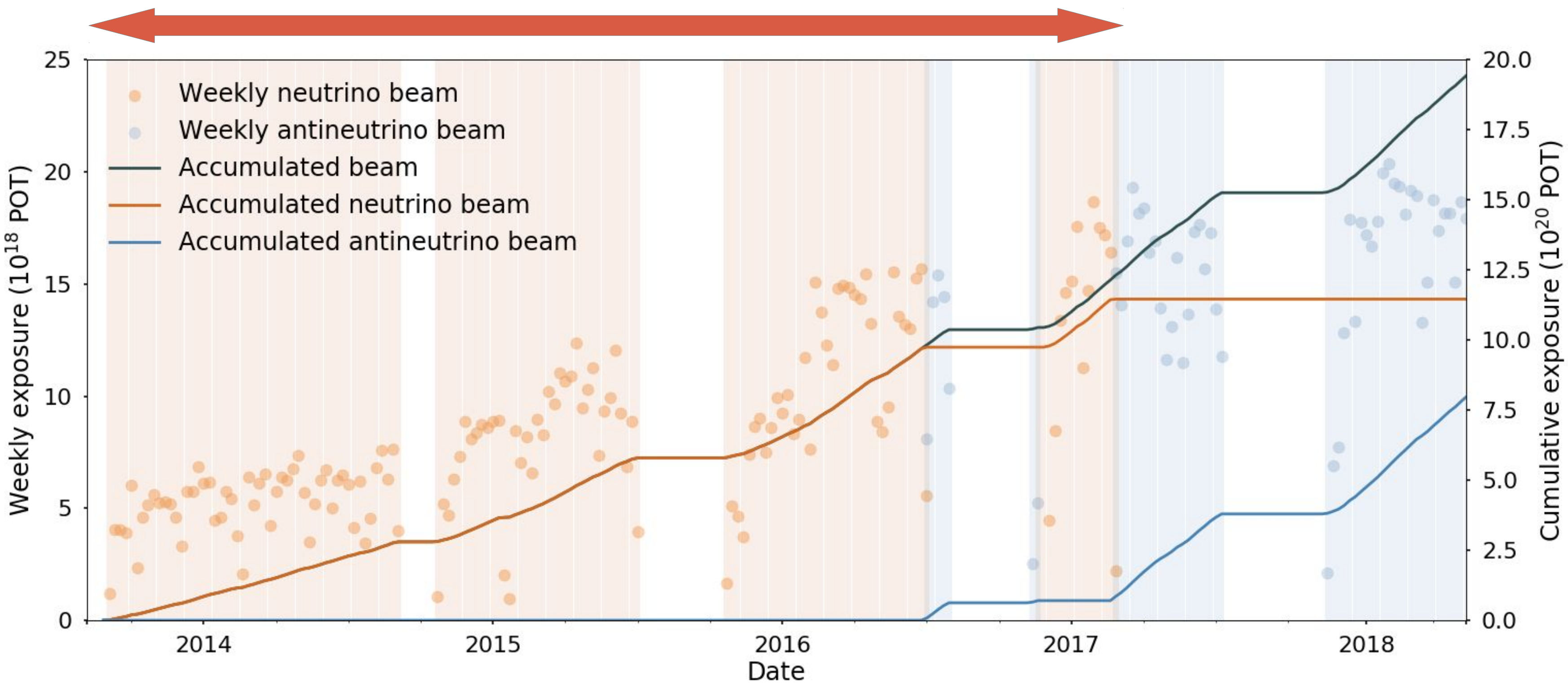


NuMI Neutrino Beam

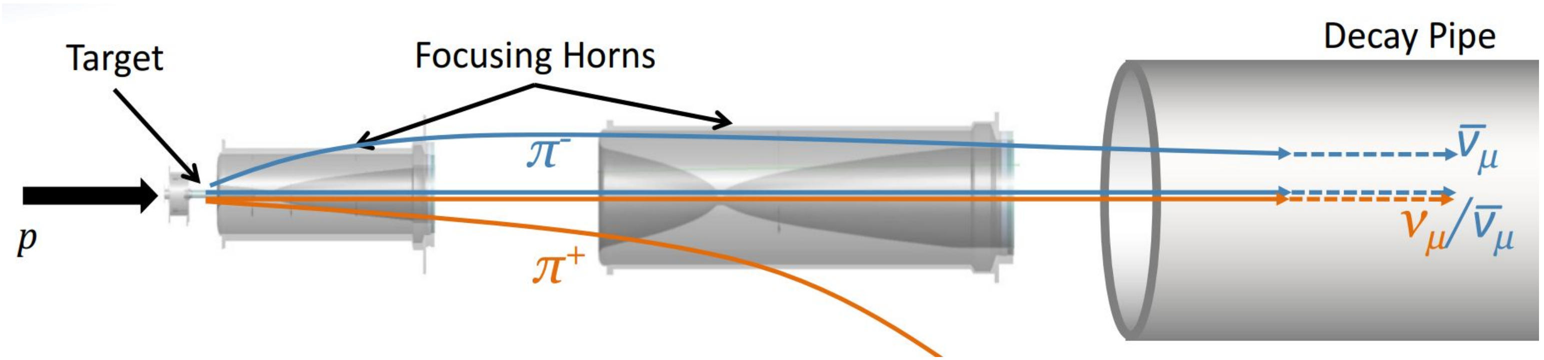


NuMI is the world's most powerful neutrino beam → running at 700 kW power since January 2017

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

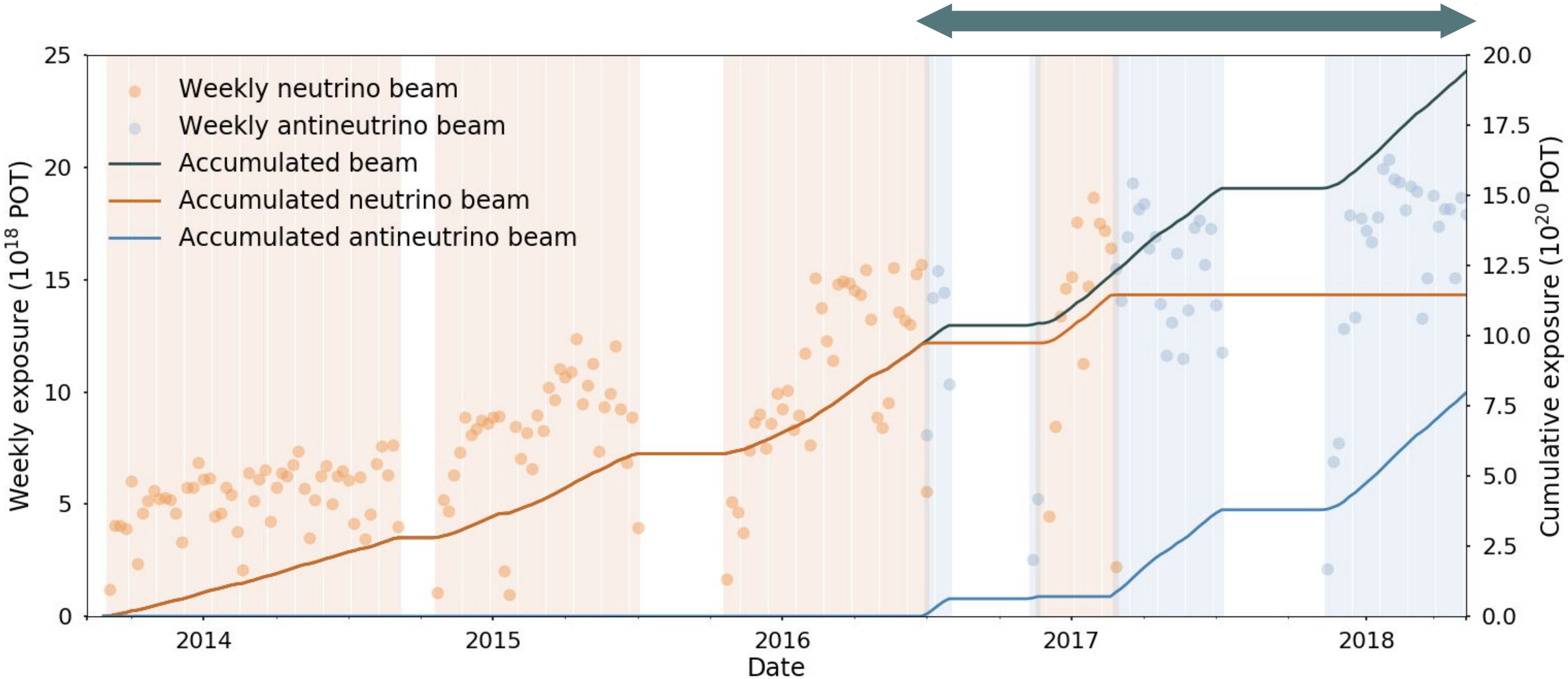


NuMI Antineutrino Beam

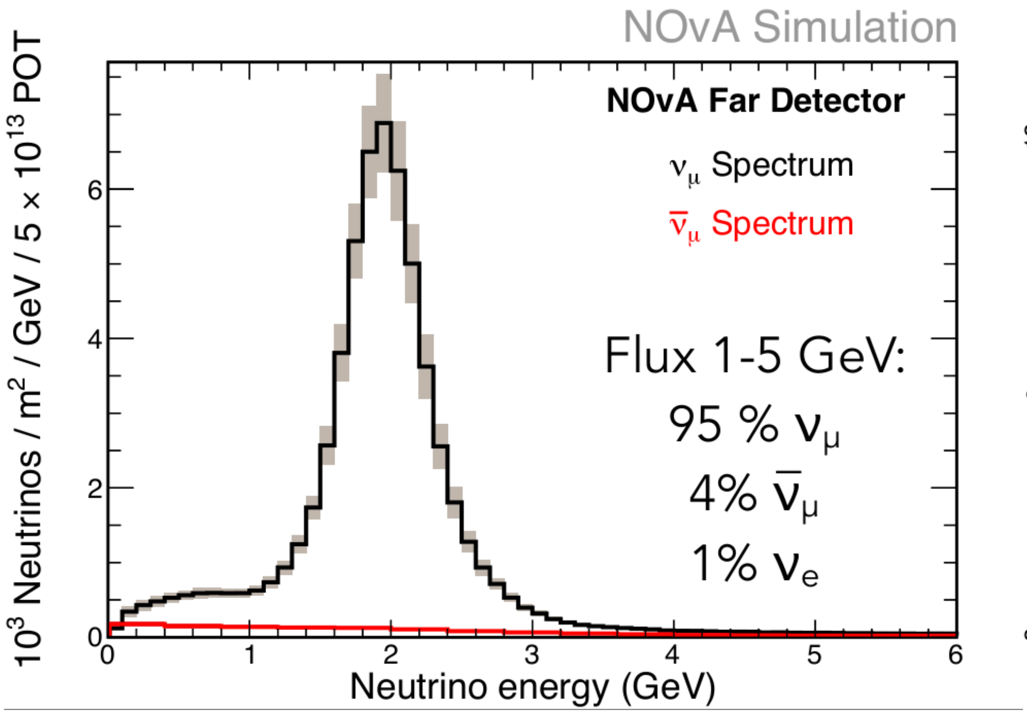


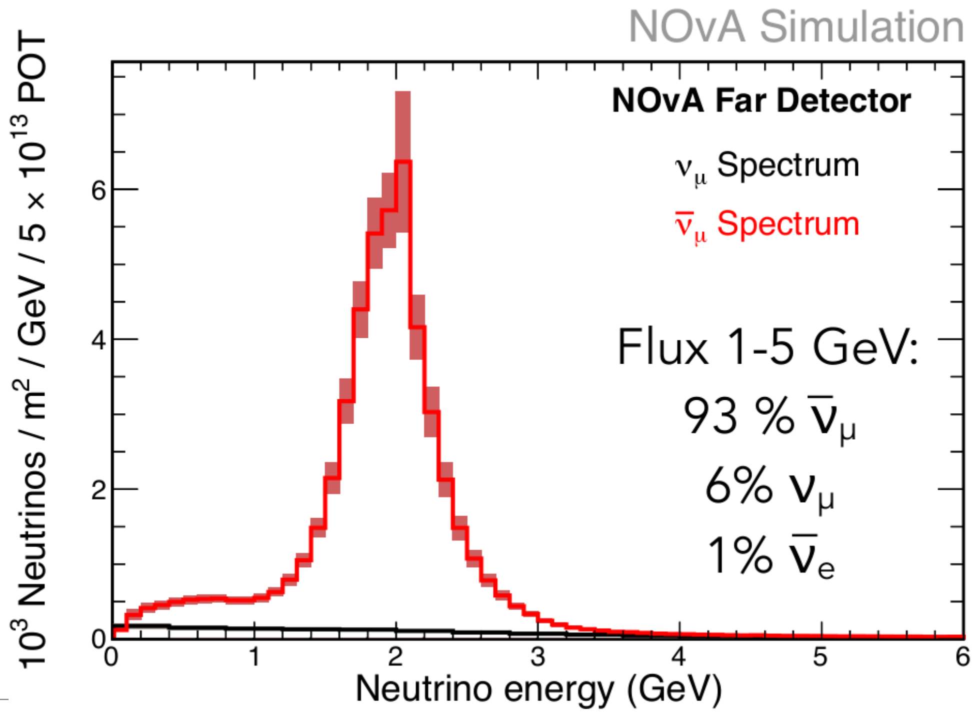
NuMI is the world's most powerful neutrino beam → running at 700 kW power since January 2017

Recorded 6.9 x 10^{20} protons on target (POT) in antineutrino mode



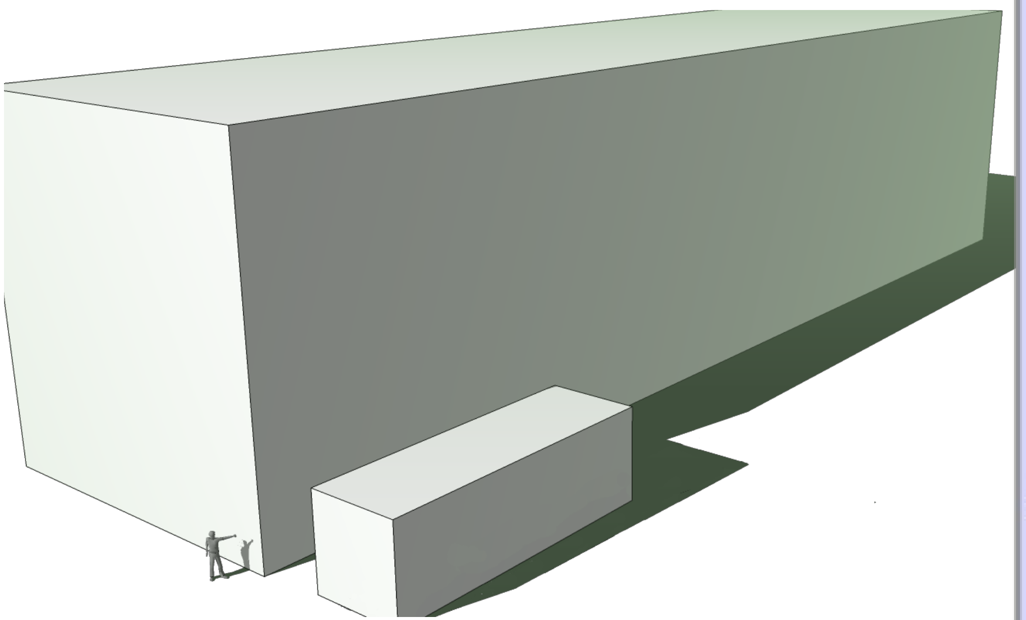
Off-axis Flux

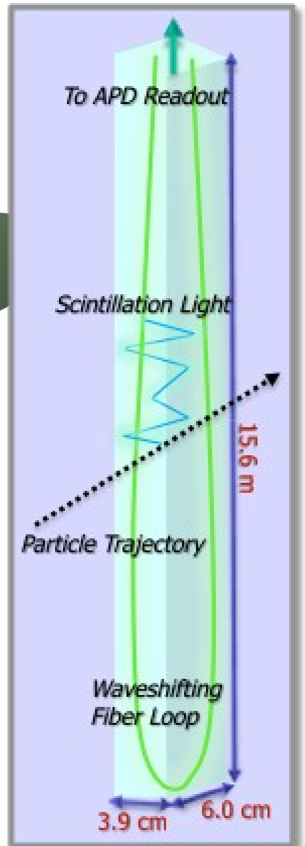




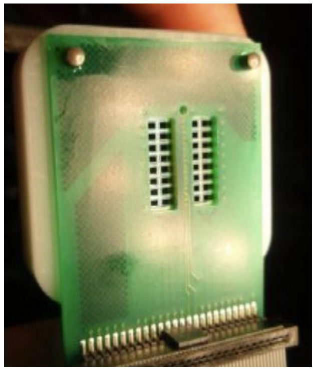
- Off-axis at 14 mrad, peaks just above the oscillation maximum. Small wrong-sign component for both configurations
- Flux prediction of the NuMI beam at the NOvA detectors made using the Package to Predict the Flux (PPFX), a method developed by MINERvA (Phys. Rev. D 94 (2006) 092005)
- Beam optics uncertainties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

NOvA Detector Design





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



Far detector (FD)

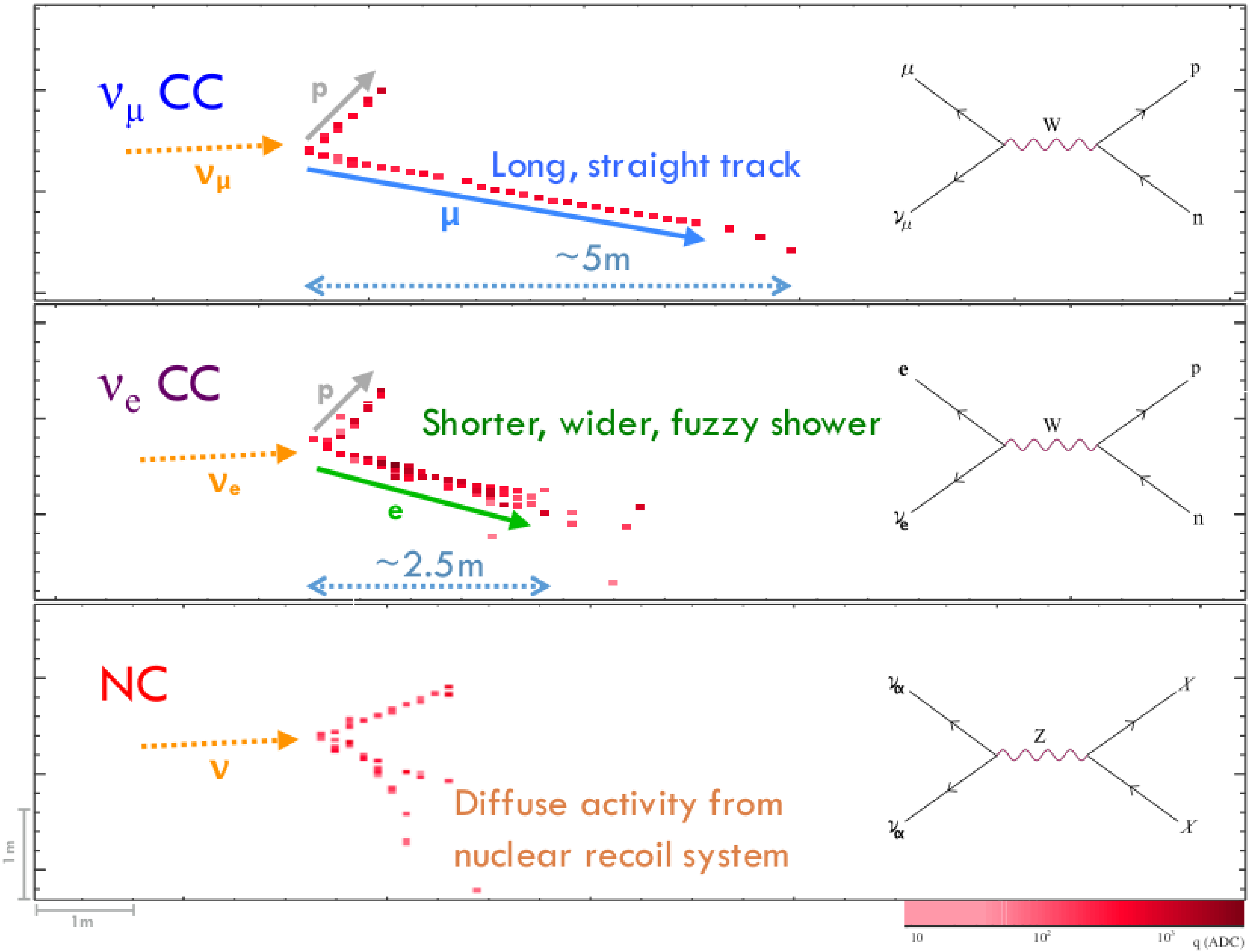
- 14 kton
- 15 m x 15 m x 60 m
- 65% active mass
- ~344,000 channels

Near detector (ND)

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

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

Event Topologies

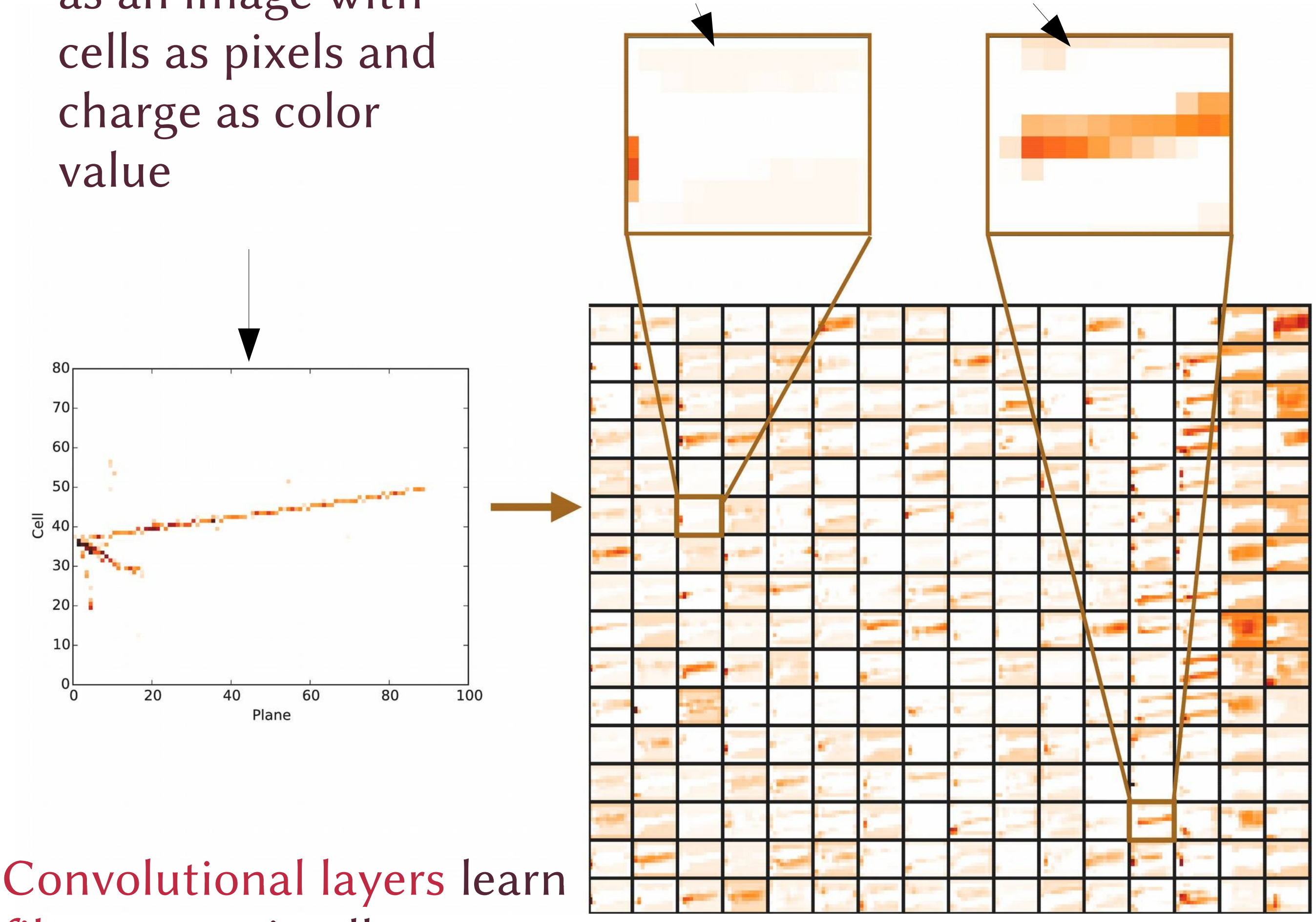


Neutrino Interaction Classifier

- 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

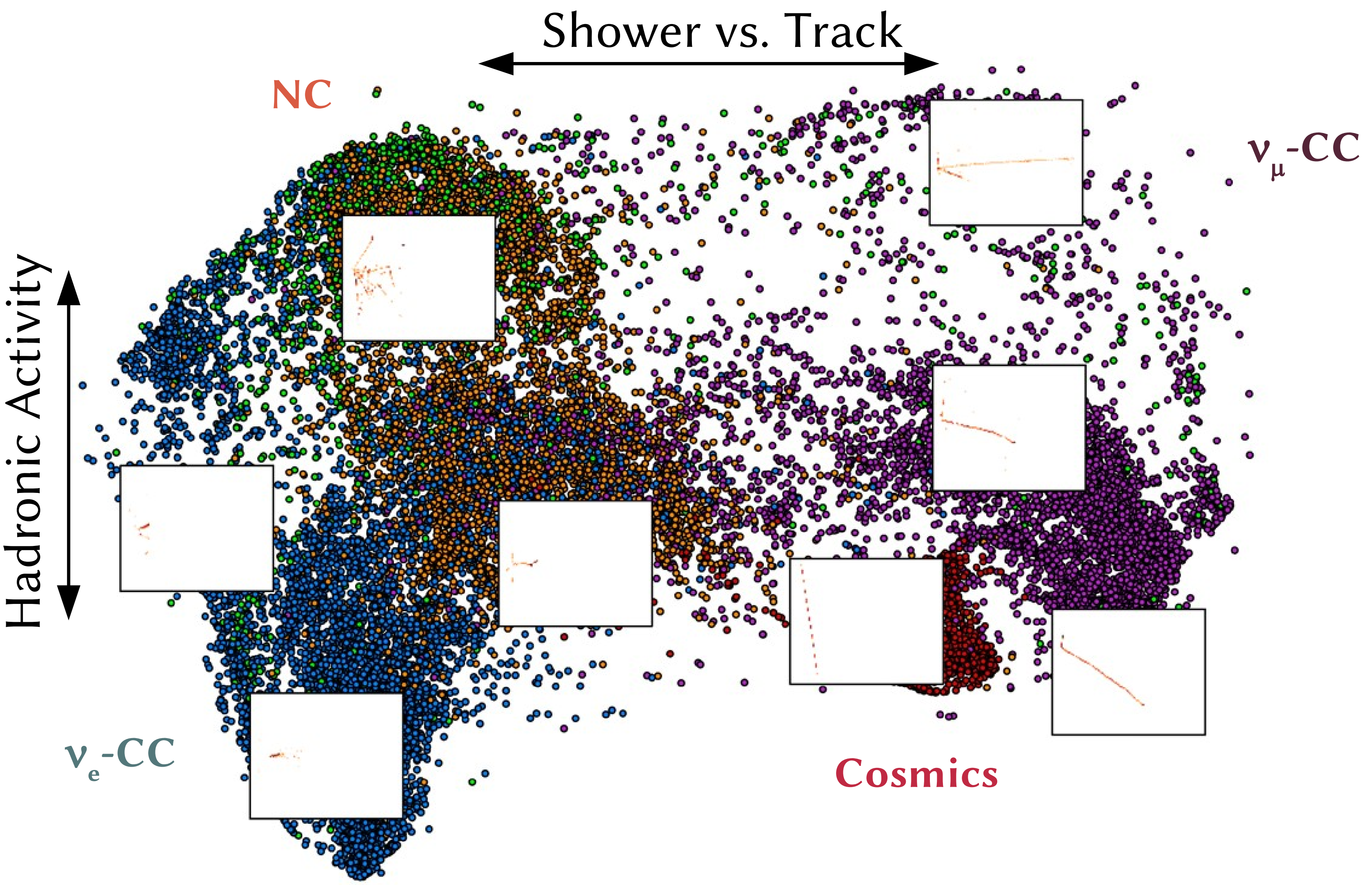
Individual learned filters are sensitive to physics: e.g. hadronic activity or muon tracks



Convolutional layers learn filters to optimally extract features from the data

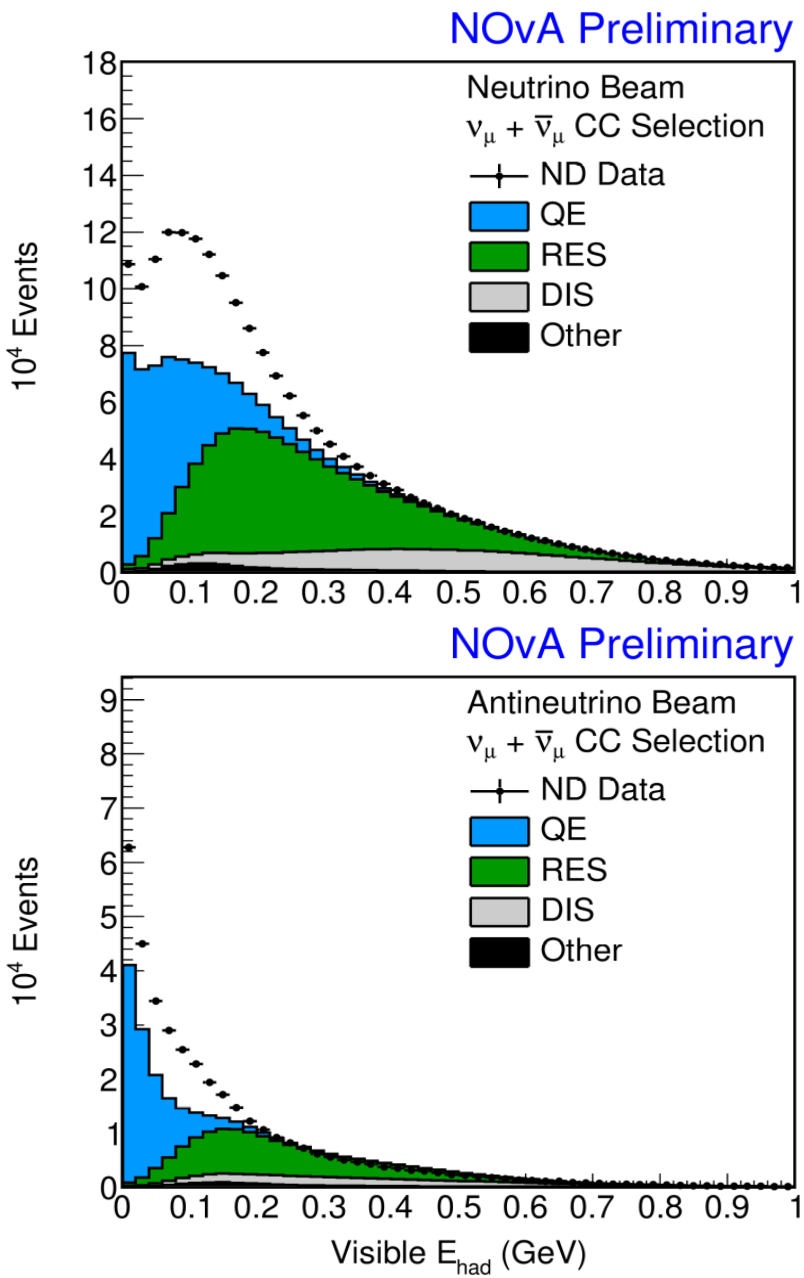
JINST 11 (2016) P09001

Neutrino Interaction Classifier



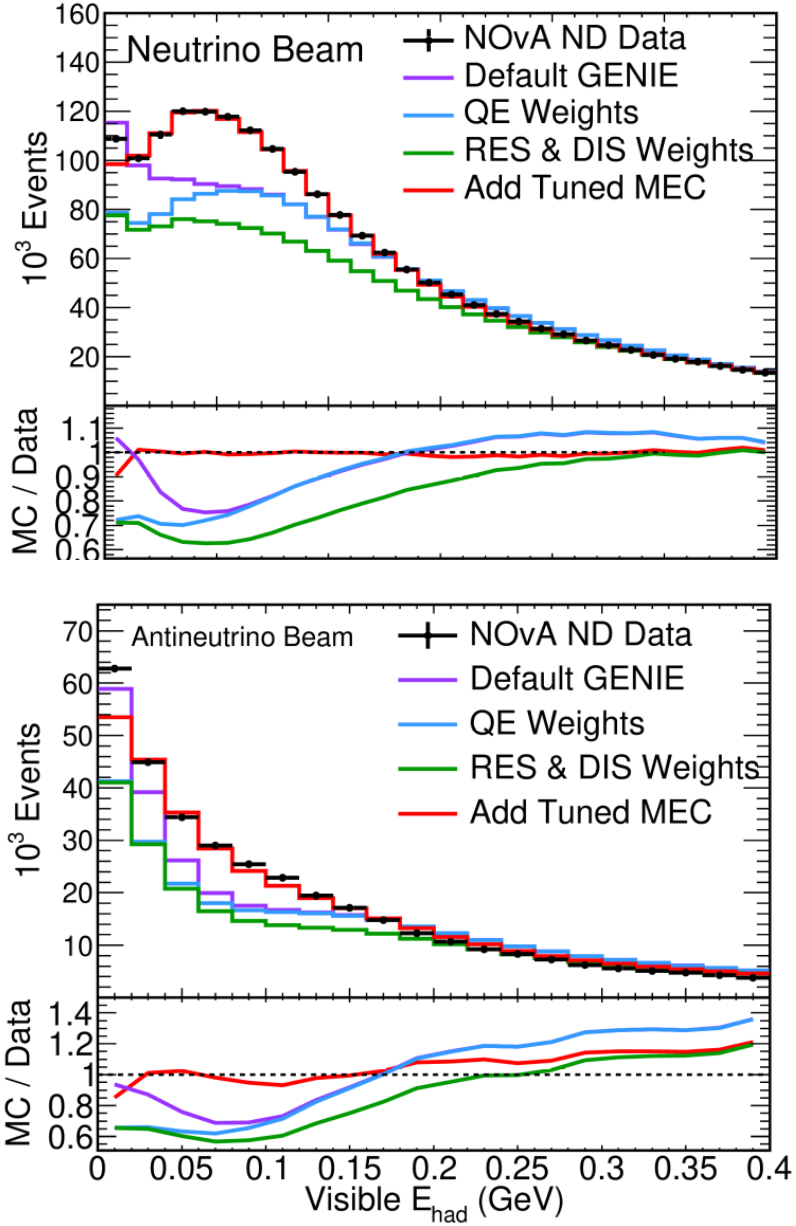
- All current oscillation analyses use this ID with different optimizations
- Trained for the neutrino and antineutrino beams separately
- Cosmic data is included in training

Neutrino Interaction Tuning



- Default GENIE prediction does not describe NOvA ND data well
  - Large discrepancies can be seen in the hadronic energy of ν_μ-CC interactions
- Likely that nuclear effects are responsible for these discrepancies
- Use a combination of external information and NOvA data to tune the model to obtain better central values and appropriate uncertainties
- Tuning is done separately for neutrino and antineutrino data

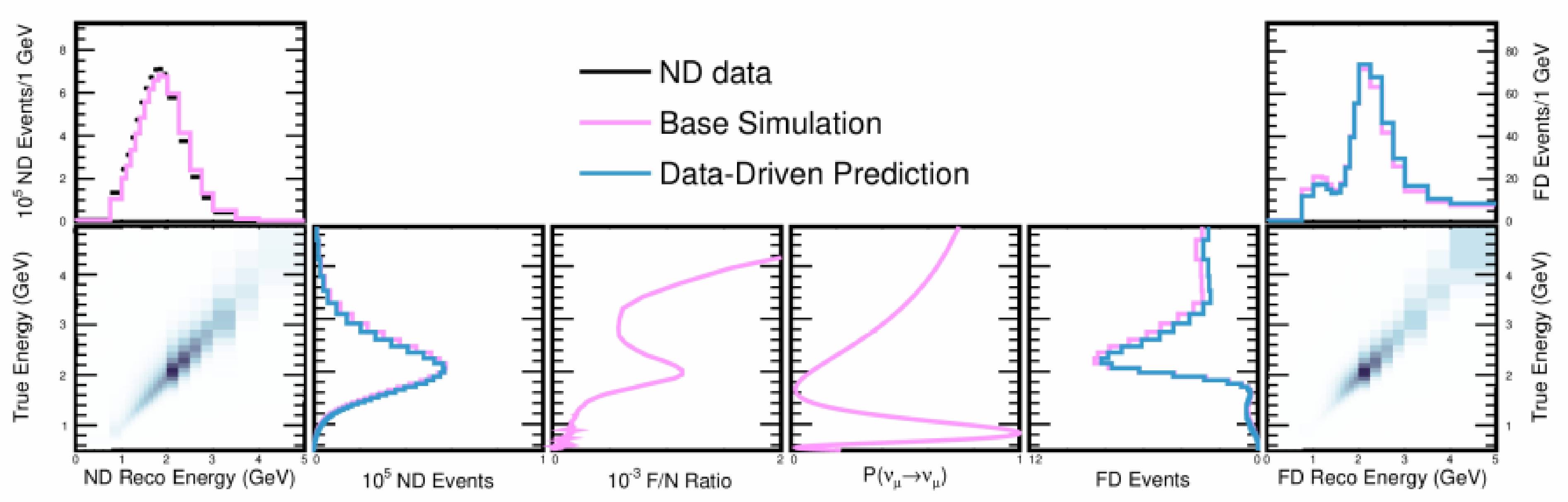
Neutrino Interaction Tuning



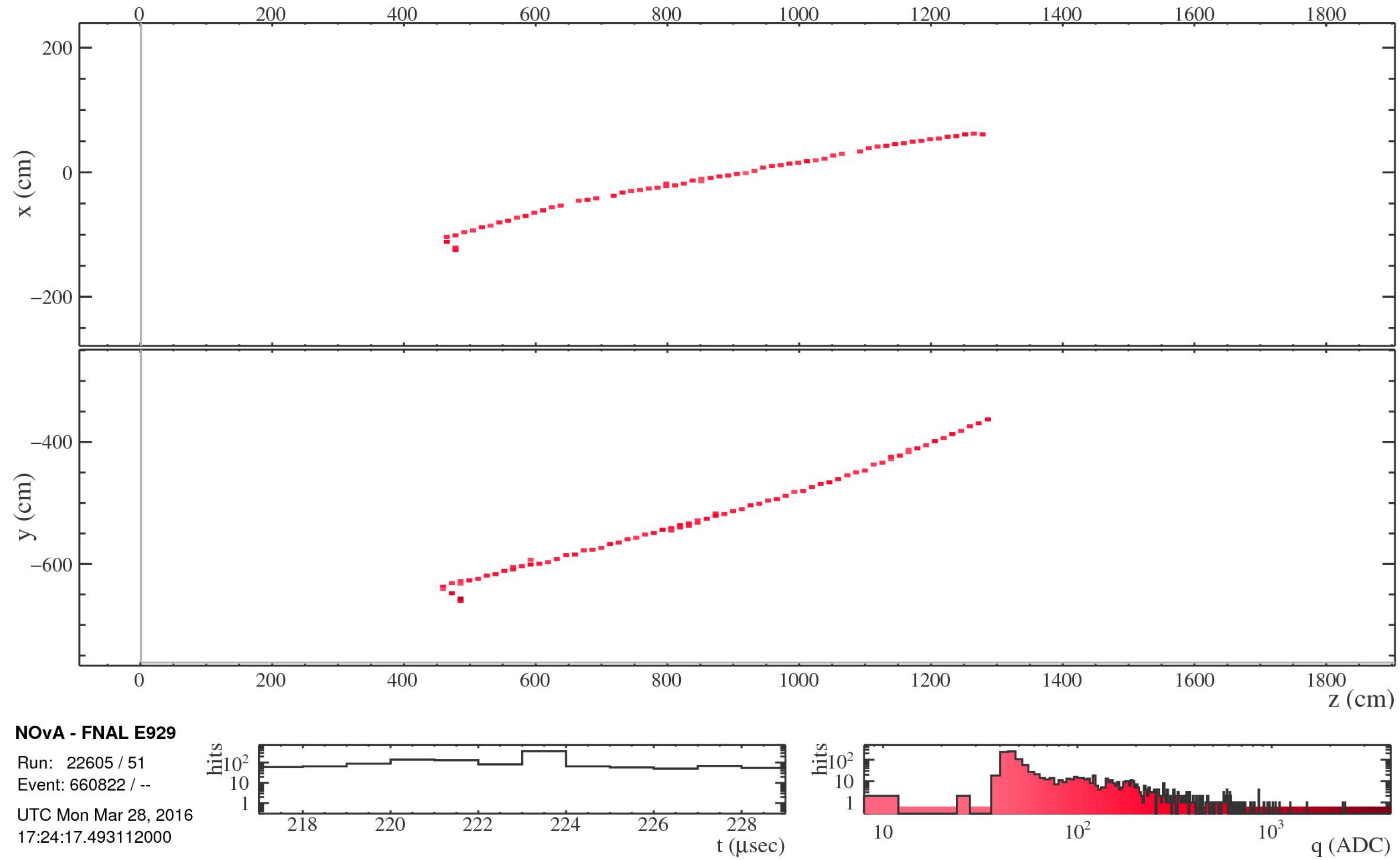
- From external information:
  - Reduce quasi-elastic (QE) component using Valencia model to account for RPA suppression
  - Apply the same long-range effect to resonant (RES) baryon production events
- From NOvA data:
  - Deep inelastic scattering (DIS) events with high invariant mass (W > 1.7 GeV/c^2) increased by 10%
  - Introduce custom tuning of GENIE "Empirical MEC" [T. Katori, AIP Conf. Proc. 1663, 030001 (2015)] model to account for multinucleon knockout (2p2h)

Far Detector Predictions

- The neutrino spectrum is measured before oscillations at the ND
  - Combination of flux, cross section, and efficiency
- The measured spectrum is used to correct the raw FD MC predictions using the Far/Near ratio
  - Each component oscillates differently, so they each are extrapolated separately
  - ND data/MC disagreements are allocated to different component either proportionally to MC predictions or using data-driven decomposition techniques
- Since the detectors are functionally similar, the combined flux and cross-section uncertainties largely cancel

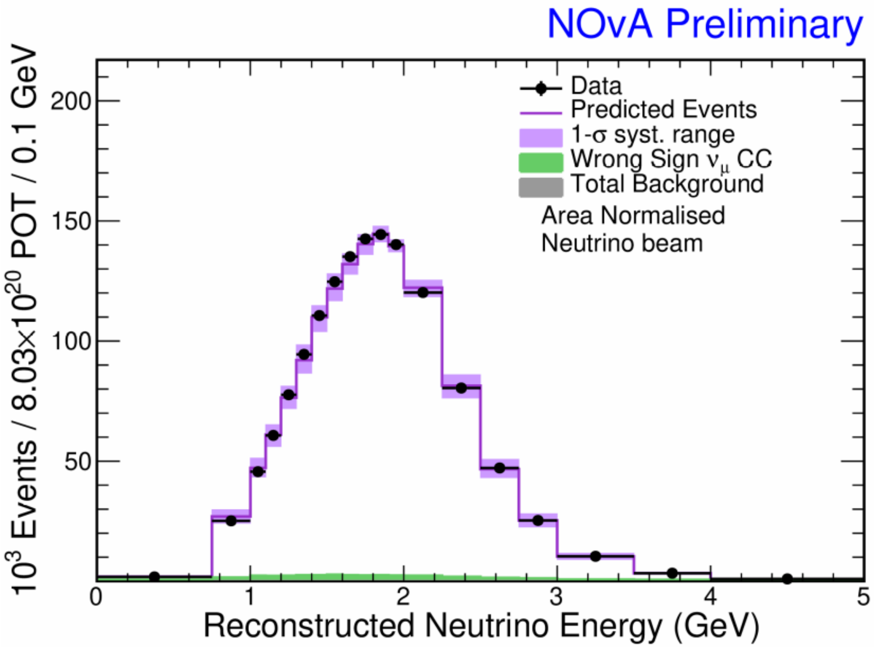


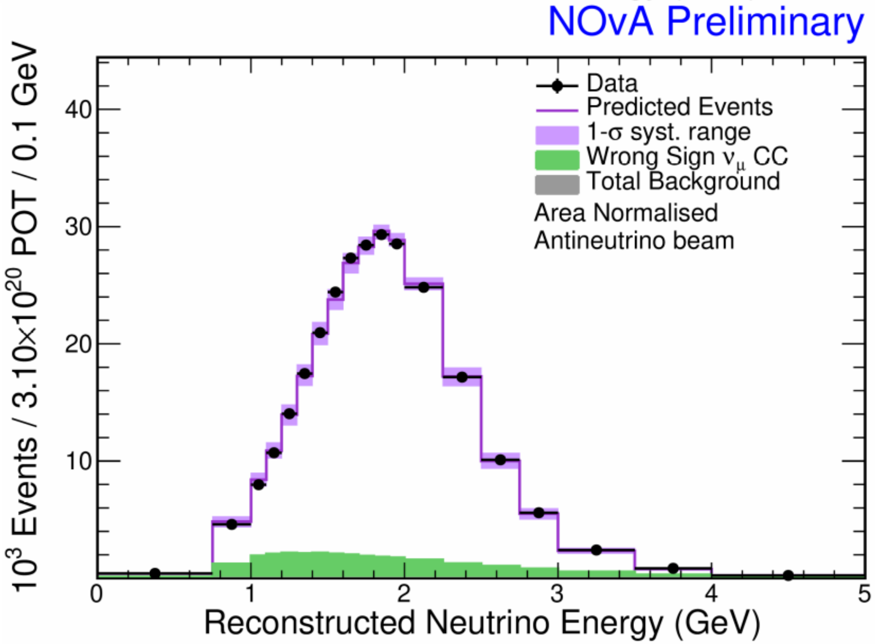
Muon Neutrino and Antineutrino Disappearance



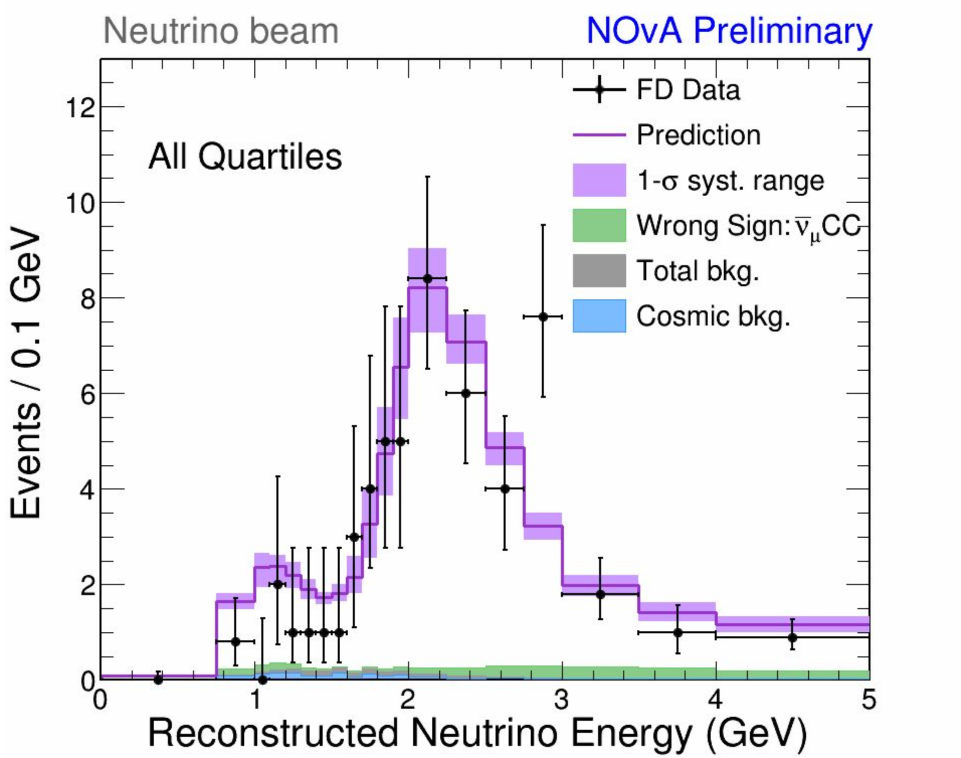
Near Detector Spectra

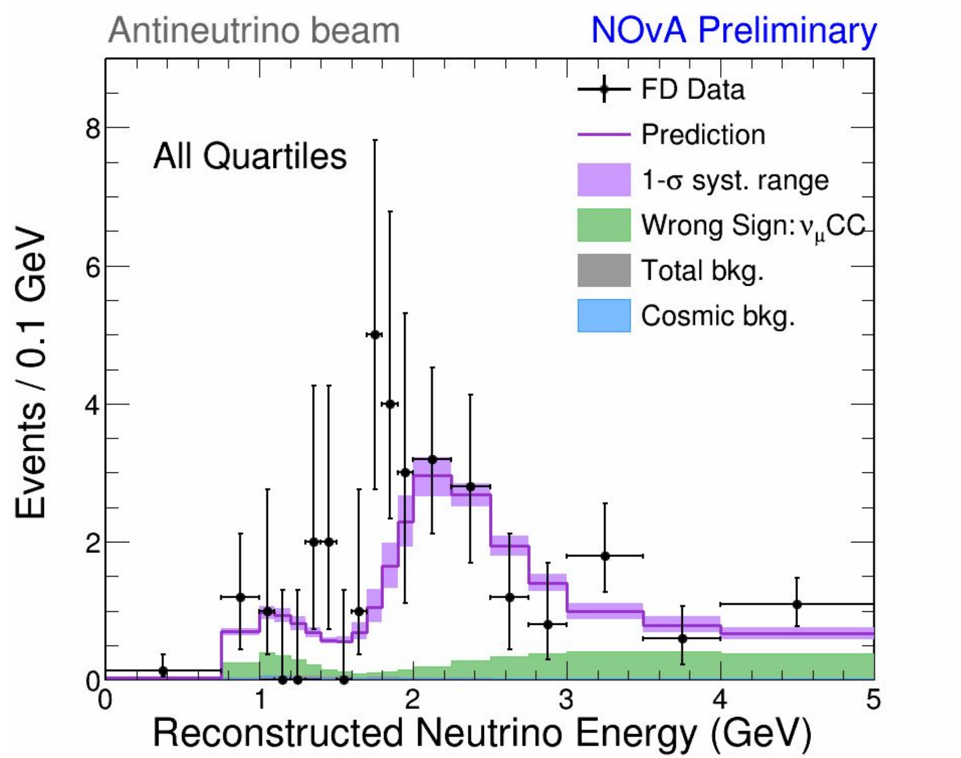
- Selected muon neutrino and antineutrino charged current interaction in ND
  - Reconstructed neutrino energy is estimated from muon length and hadronic energy
- Wrong sign contamination in ND:
  - ~3% for neutrino beam
  - ~11% for antineutrino beam
- Shape-only systematic uncertainties shown
  - 1.3% (neutrinos) and 0.5% (antineutrinos) offset removed for display purposes
- Data split into quartiles of hadronic energy fraction as a function of reconstructed neutrino energy
  - Each quartile extrapolated independently
- Energy resolution varies by quartile for the neutrino (antineutrino) beam:
  - Lowest: 5.8% (5.5%)
  - Highest: 11.7% (10.8%)





Far Detector Observed Events

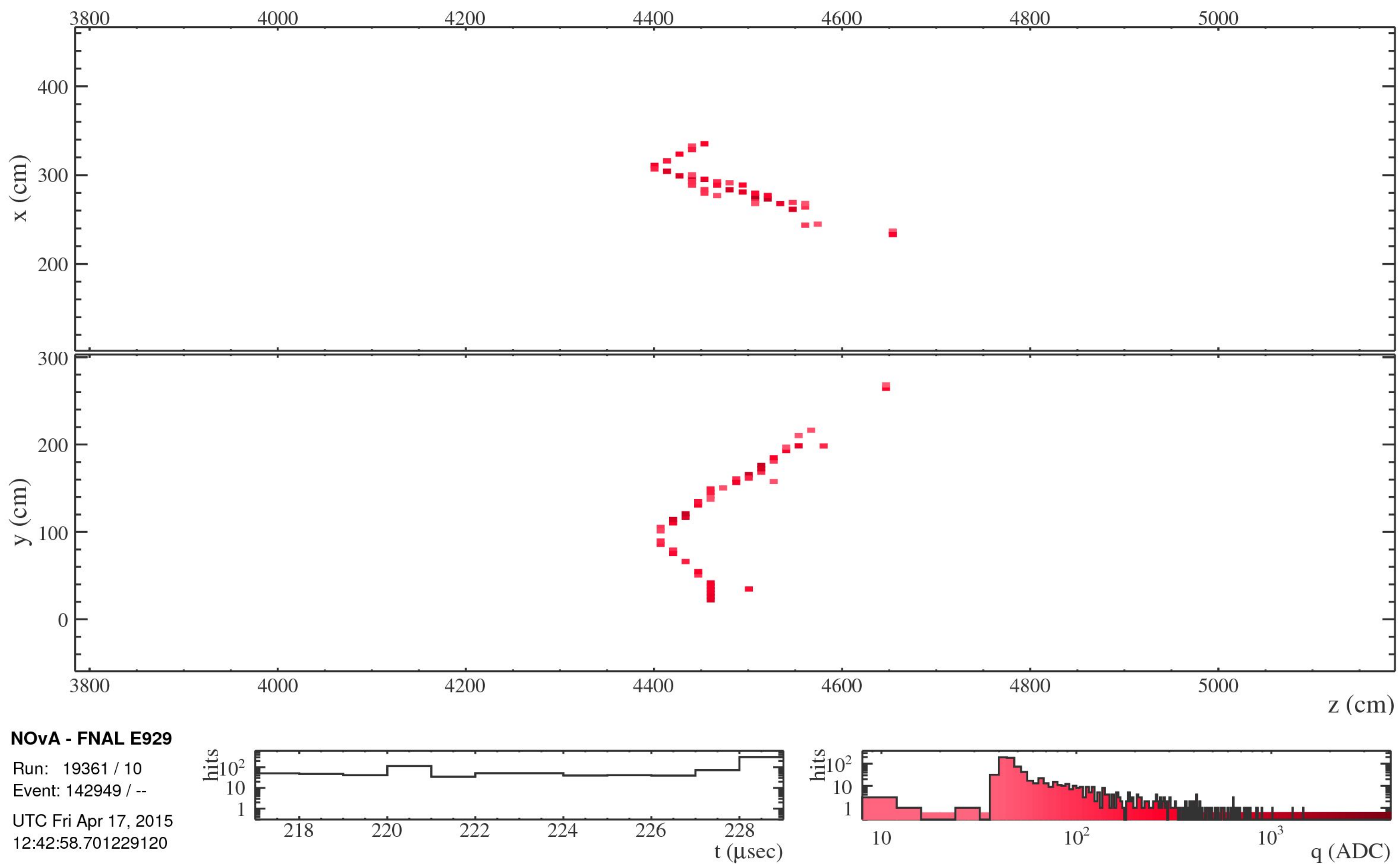




Total observed	113
Prediction at best fit	121
Cosmic background	2.1
Beam background	1.2
Unoscillated prediction	730

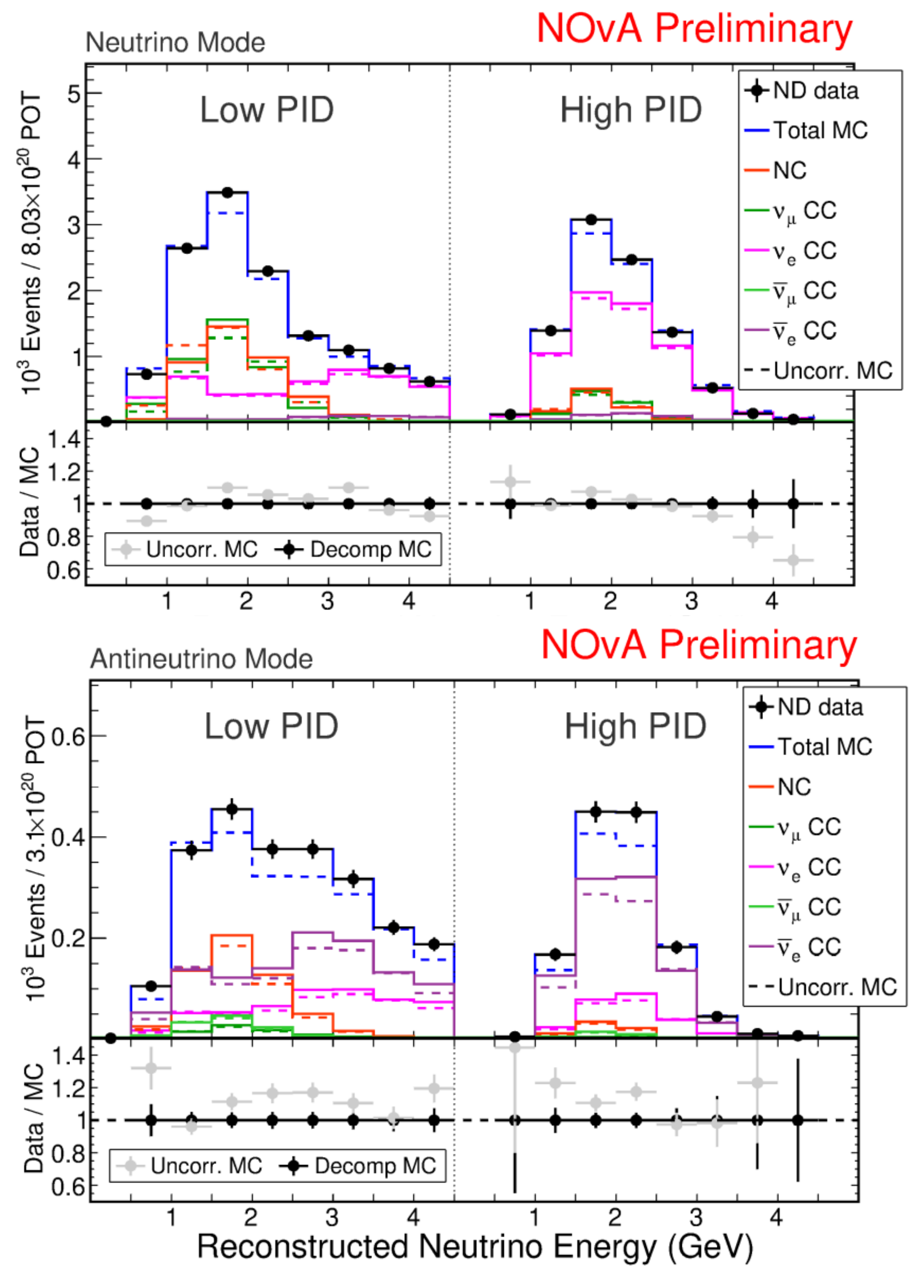
Total observed	65
Prediction at best fit	50
Cosmic background	0.5
Beam background	0.6
Unoscillated prediction	266

Electron Neutrino and Antineutrino Appearance



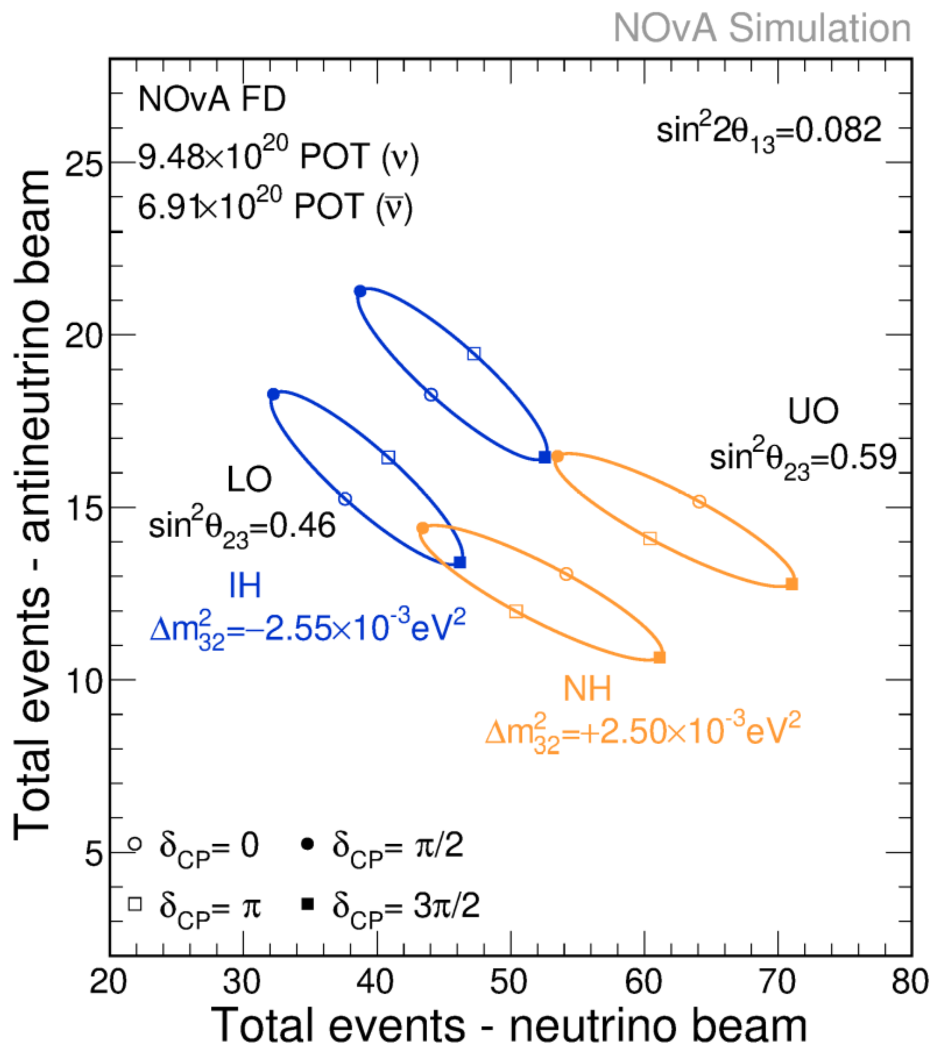
Near Detector Spectra

- Select electron neutrino events using CVN in the ND for each beam mode
  - Separate into low and high CVN ranges
- For the neutrino beam, constrain:
  - Beam electron neutrinos using the muon neutrino spectrum
  - Muon neutrino background using Michel electrons
- The remaining data/MC disagreement is assigned to the NC component
- For the antineutrino beam, scale all components proportionally to match the data
- Corrected ND spectra are used to predict the background in the FD
- Each component is propagated independently in bins of energy and CVN
  - One "peripheral" bin is added for the FD for events with high CVN but only pass a less stringent containment selection



Electron Neutrino Appearance Expectations

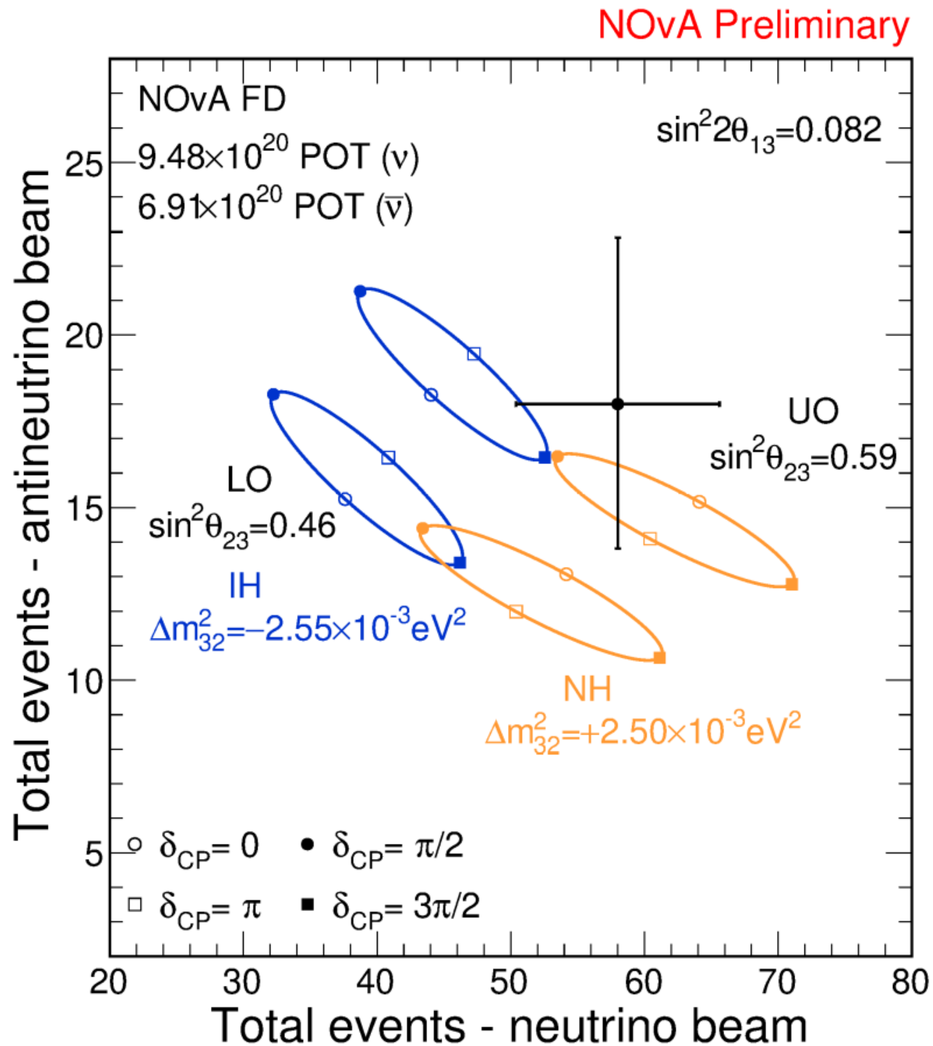
- Event counts in neutrino and antineutrino mode vary according to the oscillation parameters
- Ellipses show the dependence of the prediction on δ_{CP} for the normal (NH) and inverted hierarchy (IH) as well as upper (UO) and lower (LO) octants



Expect 30-75 events for neutrino mode and 10-22 for antineutrino mode

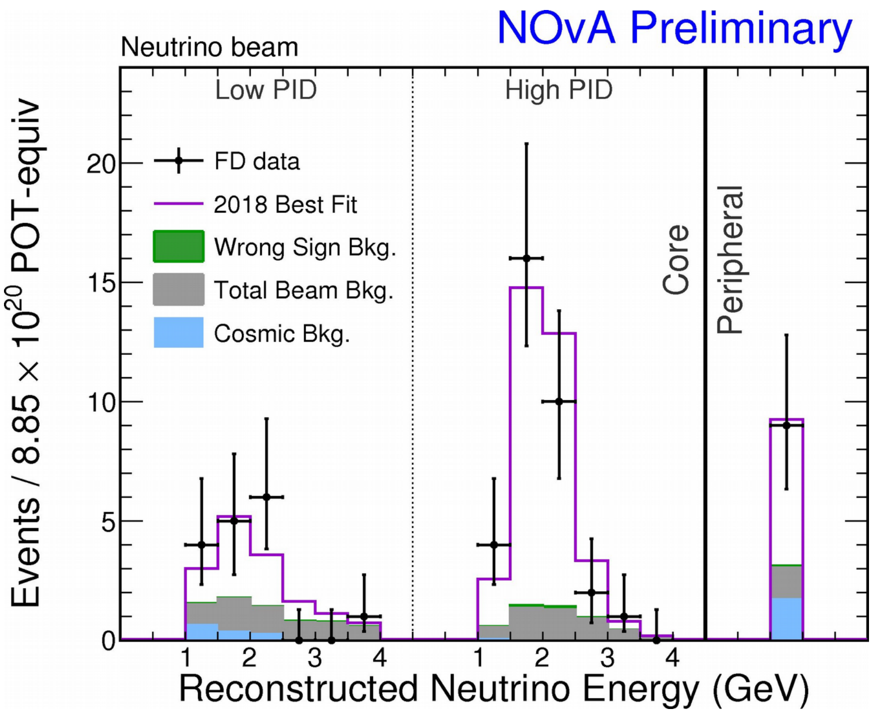
Electron Neutrino Appearance Expectations

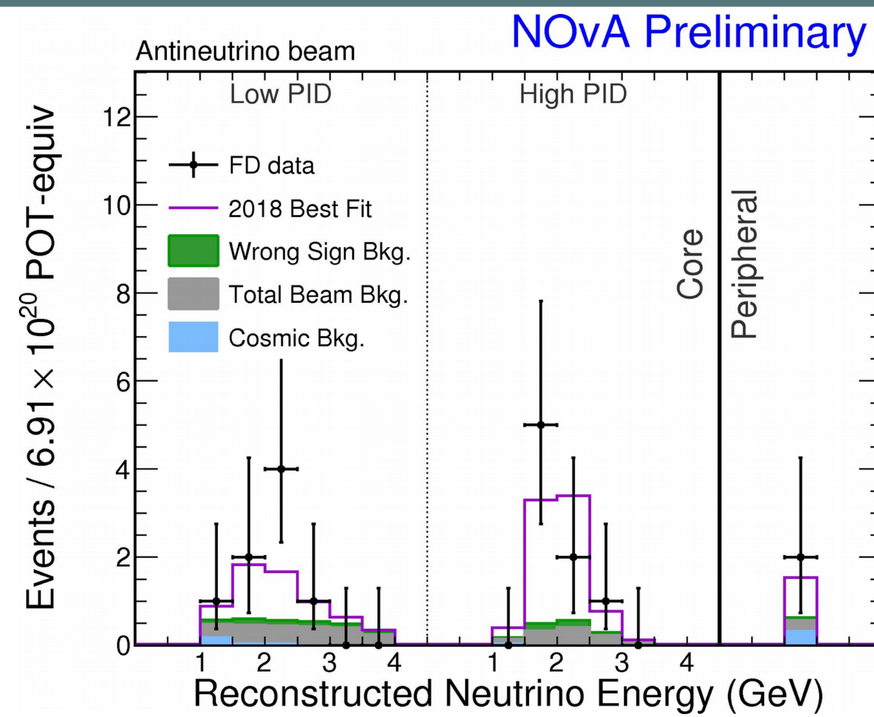
- Event counts in neutrino and antineutrino mode vary according to the oscillation parameters
- Ellipses show the dependence of the prediction on δ_{CP} for the normal (NH) and inverted hierarchy (IH) as well as upper (UO) and lower (LO) octants



NOvA observes 58 events for neutrino mode and 18 in antineutrino mode

Far Detector Observed Events





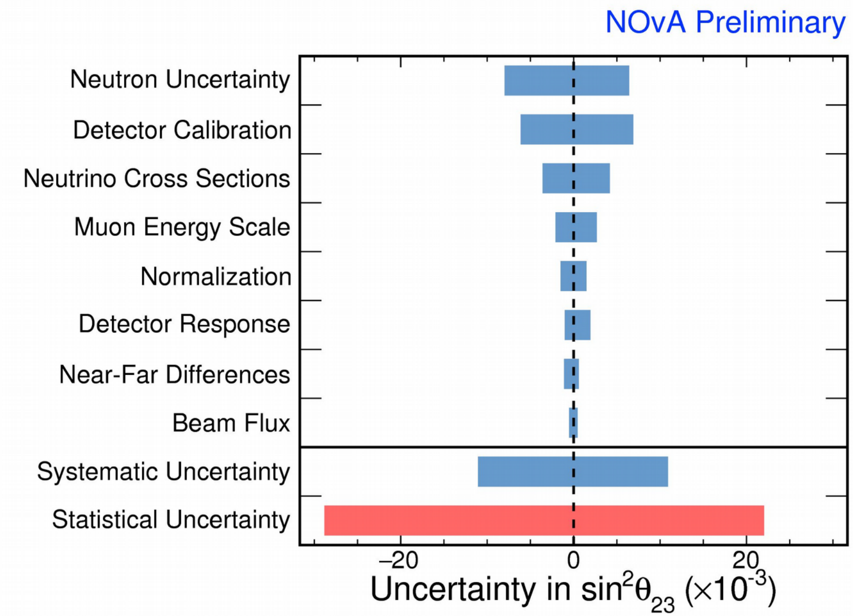
Total observed	58
Prediction at best fit	59
App. Electron neutrino	44
App. Electron antineutrino	0.7
Cosmic background	3.3
Other beam bkg	7.9

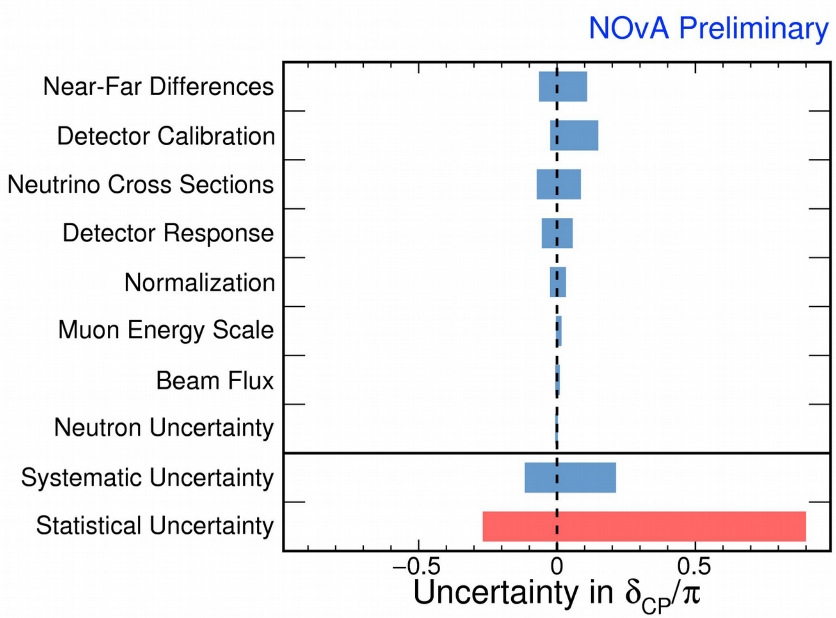
Total observed	18
Prediction at best fit	16
App. Electron antineutrino	11
App. Electron neutrino	1.1
Cosmic background	0.7
Other beam bkg.	2.8

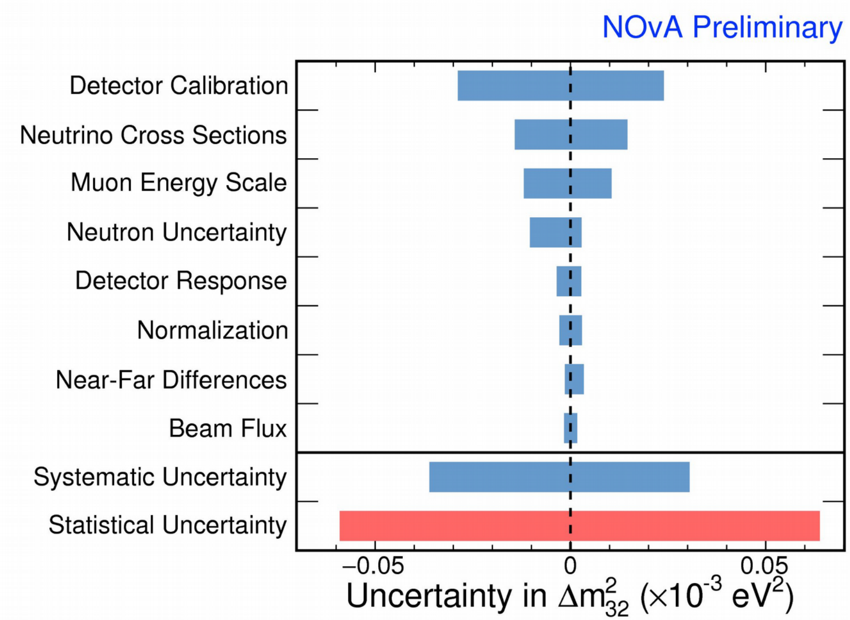
First evidence (> 4σ) of $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam

Systematic Uncertainties

- Limited by statistical uncertainty
- Most important systematic uncertainties: detector calibration and neutrino interactions
- Neutron uncertainty also large in antineutrino mode

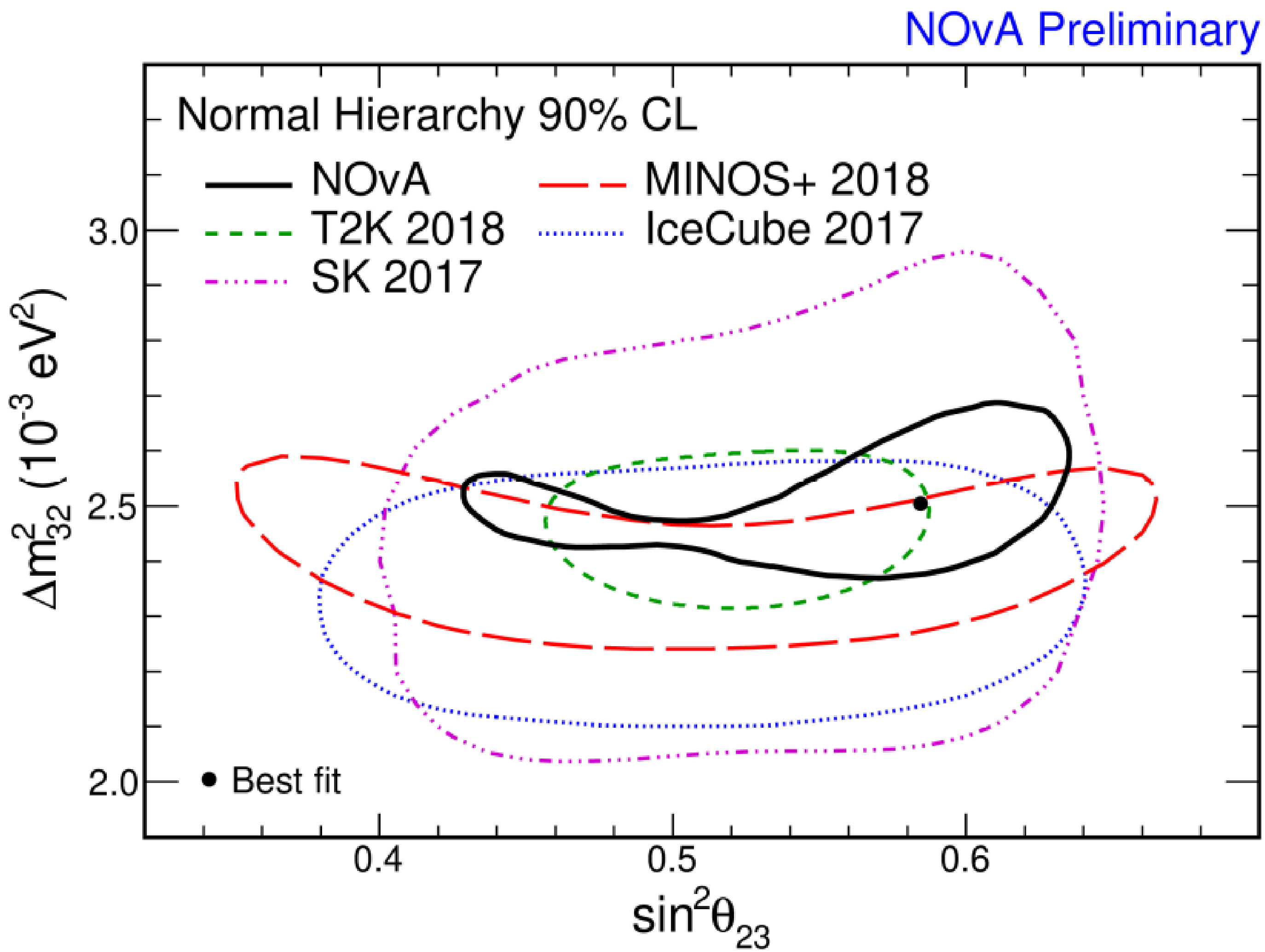






Joint Fit Results

Consistent with other long-baseline and atmospheric neutrino experiments



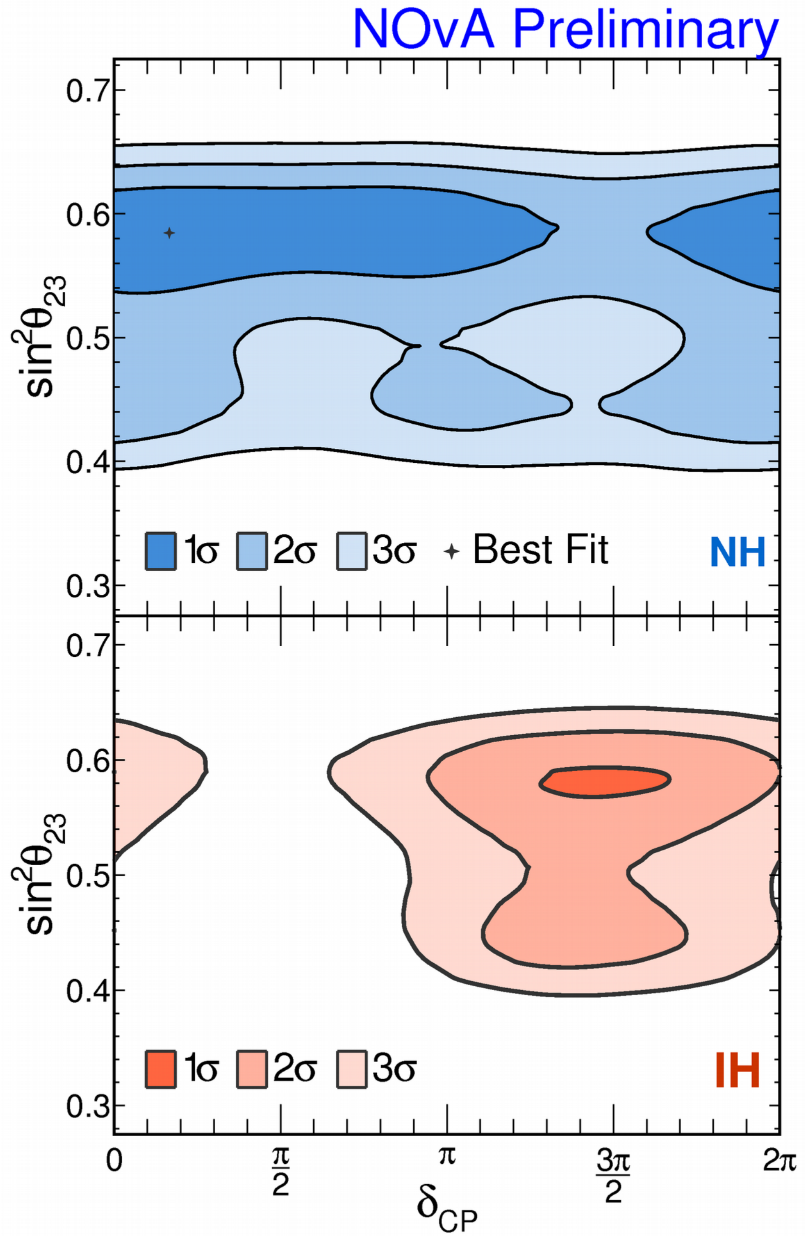
Joint Fit Results

Best fit:

$$\delta_{\rm CP} = 0.17\pi$$

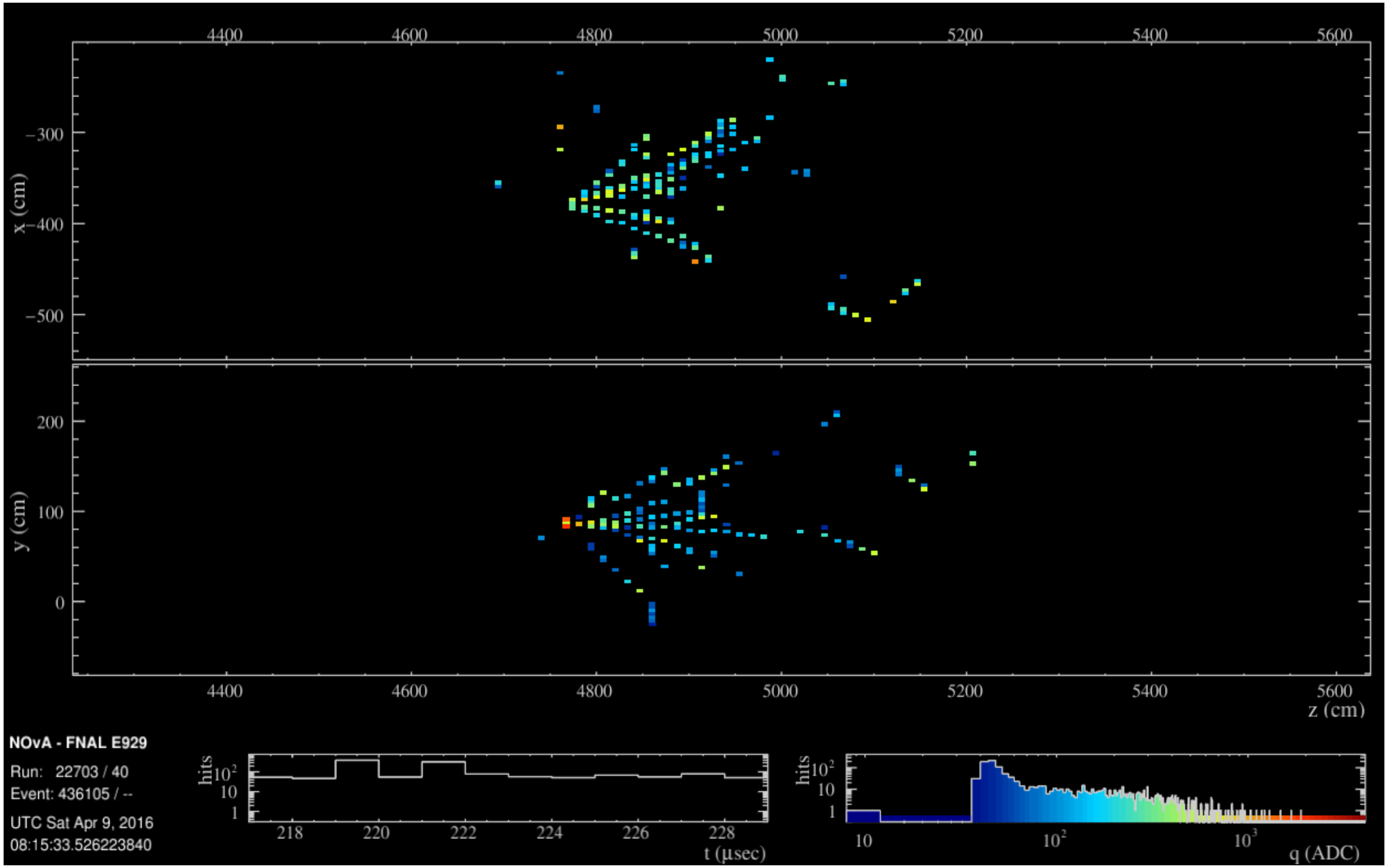
$$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3} {\rm eV}^2$$

$$\sin^2\theta_{23} = 0.58 \pm 0.03$$

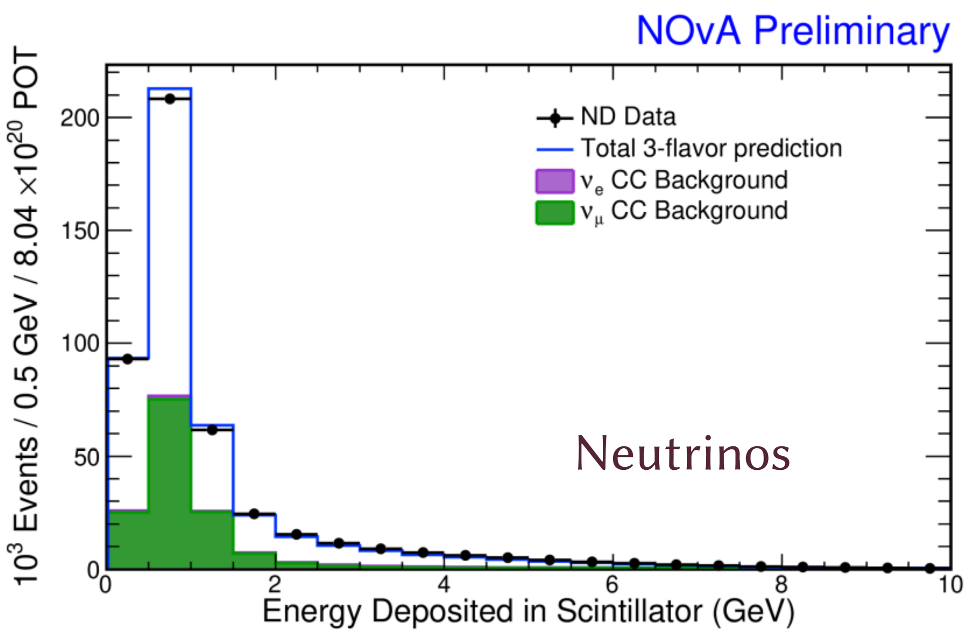


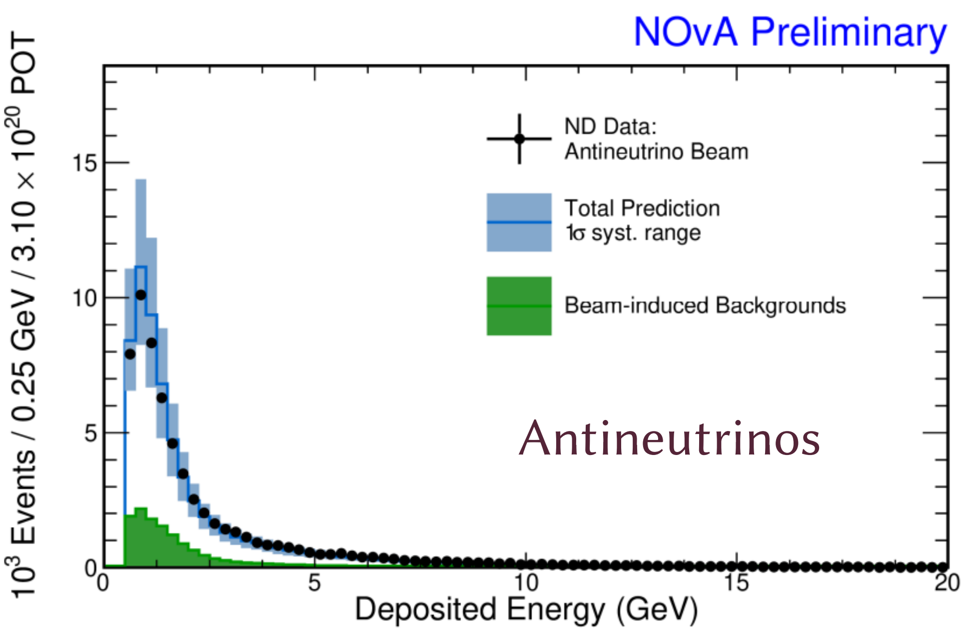
- Prefer NH at 1.8σ
- Exclude $\delta_{CP} = \pi/2$ in IH at > 3σ
- Disfavor maximal mixing at 1.8σ and LO at a similar level

Neutrino and Antineutrino Neutral Current Disappearance



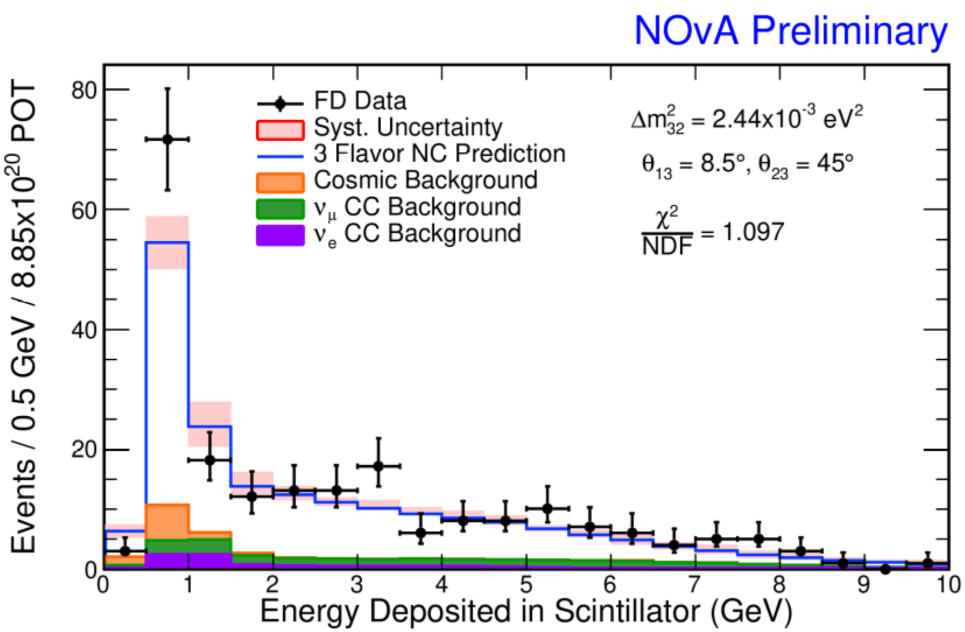
Near Detector Spectra

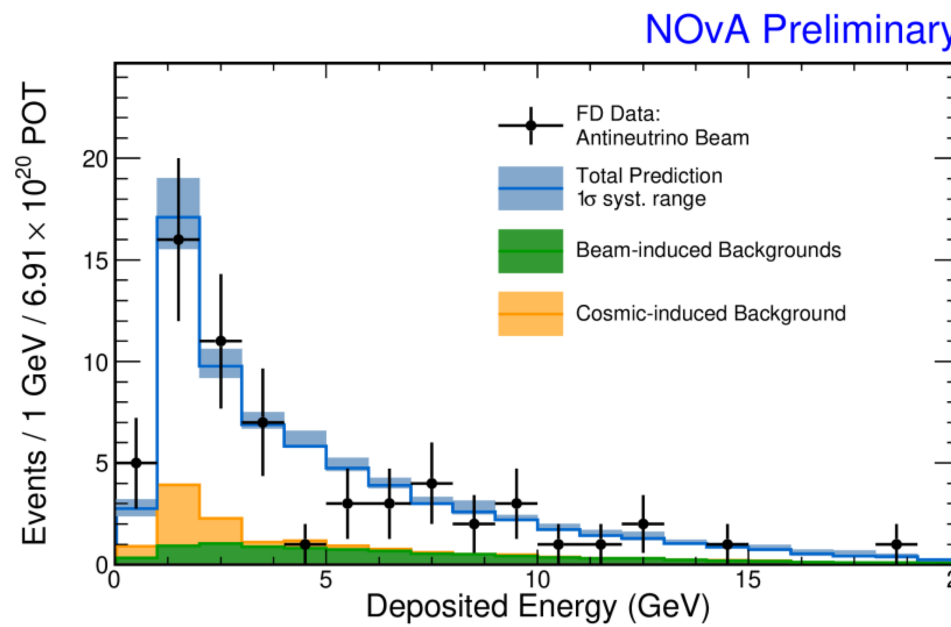




- CVN selector excellent at separating NC signal from beam backgrounds
- Good data/MC agreement in the ND in both the neutrino and antineutrino beams
- In general sterile models, oscillations can occur at short baselines
  - Restrict to $0.05 < \Delta m^2_{41} < 0.5$ eV^2 so that ND oscillations are negligible
- Scale each component proportionally to account for any data/MC disagreements in the ND

Far Detector Spectra

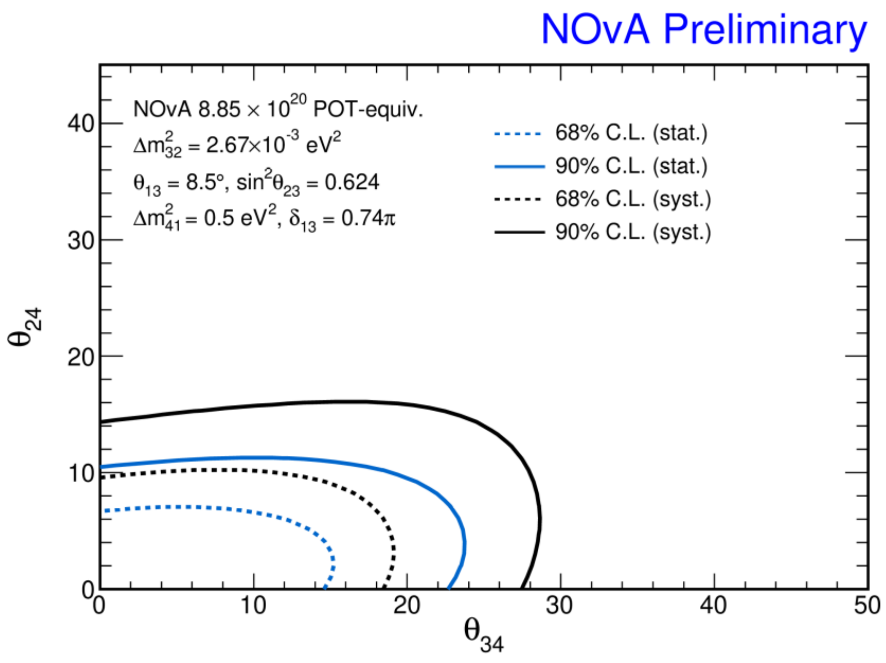


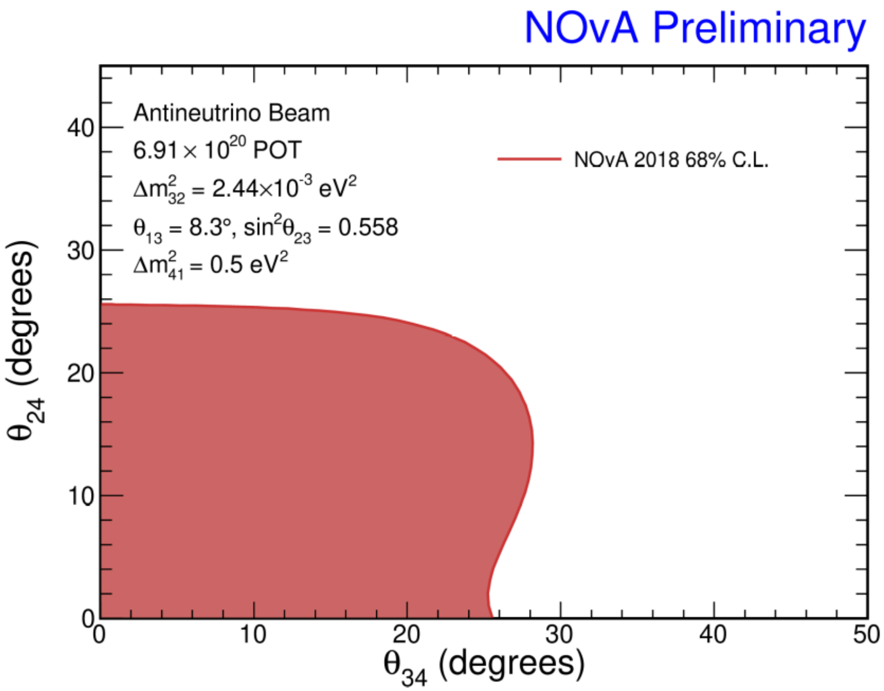


- Neutrino data:
  - Predicted **191.2 ± 13.8 (stat) ± 22.0** (syst) events
  - Observed **214** events
- Antineutrino data:
  - Predicted **69 ± 8 (stat) ± 10 (syst)** events
  - Observed **61** events

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

Neutrino and Antineutrino Limits



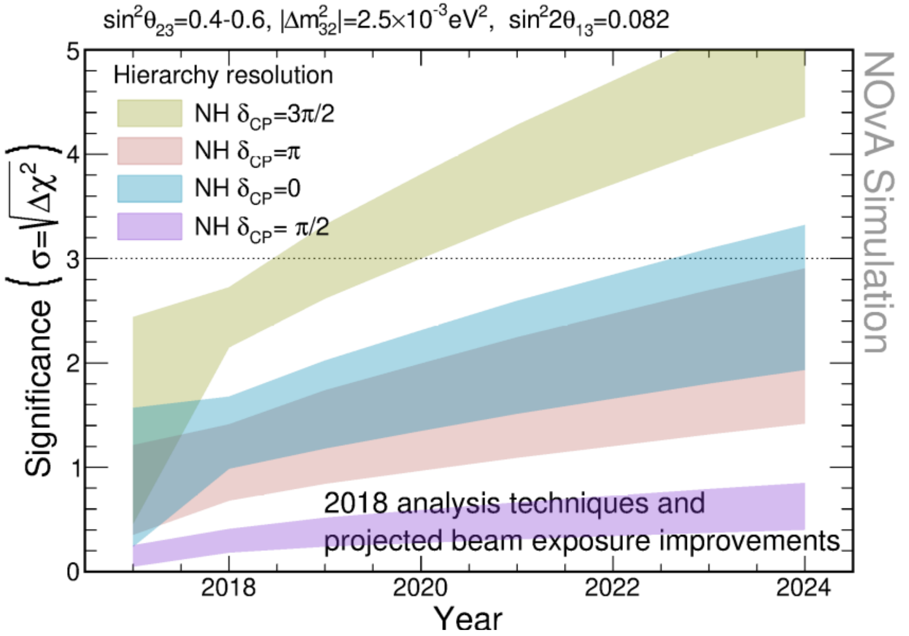


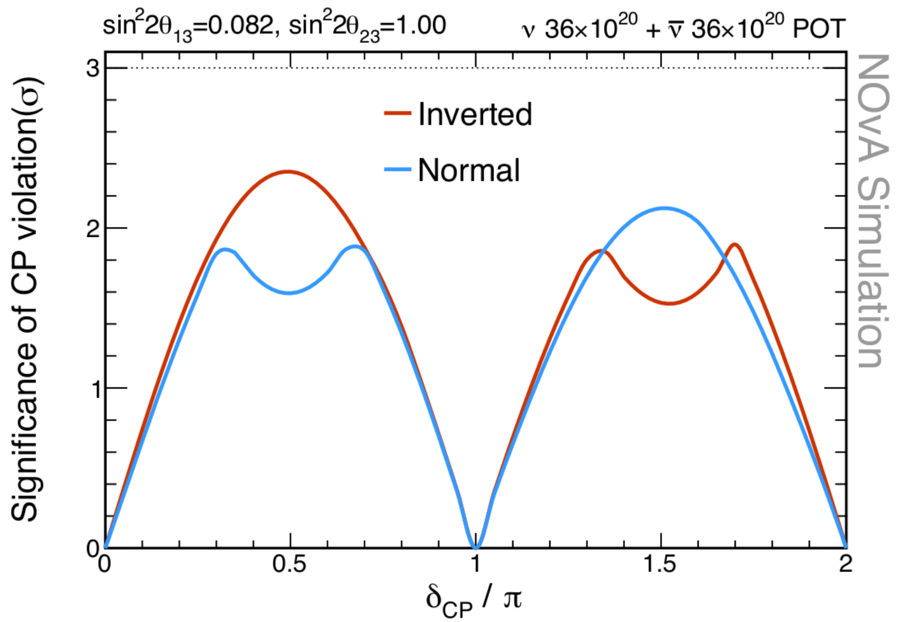
- 1D 90% CL limits at $\Delta m_{41}^2 = 0.5\ eV^2$:
  - $\theta_{24} < 16.2^o$
  - $\theta_{34} < 29.8^o$
- 1D 68% CL limits at $\Delta m_{41}^2 = 0.5\ eV^2$:
  - $\theta_{24} < 25.5^o$
  - $\theta_{34} < 31.5^o$

The Future

Prospects

- Accumulated extra ~5.6×10^{20} POT in antineutrino mode between April 2018 and February 2019
- Switched to neutrino mode at the end of February
  - Plan to run 50:50 for the future
- Final datasets will have exposures of 36×10^{20} POT for both beam modes by 2024, assuming planned accelerator upgrades
- Assuming current techniques:
  - 3σ sensitivity to hierarchy for favorable parameters by 2020
  - 3σ sensitivity for 30-50% (depending on octant) of δ_{CP} range by 2024
  - Assuming unknown hierarchy, 2σ sensitivity to CP violation for favorable parameters by 2024





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, beamline fully aligned as of this week
- Operations starting ~April, planning on 2 million particles

Summary

- First 6.9×10^{20} POT of antineutrino data has been analyzed together with 8.85×10^{20} POT of neutrino data
  - An addition ~5.6×10^{20} POT of antineutrino has been collected
- Observe >4σ evidence of electron antineutrino appearance
- Joint appearance and disappearance analysis for these data:
  - Prefers NH at 1.8σ and excludes $\delta_{CP} = \pi/2$ at > 3σ for the IH
  - Rejects maximal mixing at 1.8σ and the lower octant at a similar level
- 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, 68% CL
    - $\theta_{24} < 25.5°$, $\theta_{34} < 31.5°$
- Future NOvA running can reach 3σ sensitivity for the mass hierarchy by 2020 and covers significant δ_{CP} range by 2024
- Further improvements are possible due to detector response and calibration improvements from the upcoming test beam program

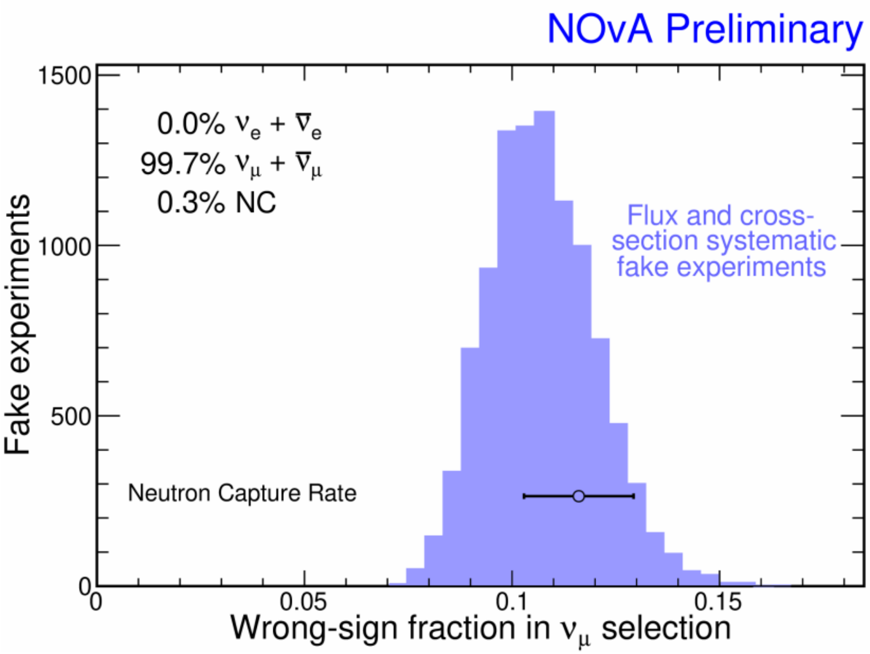
Thank You!

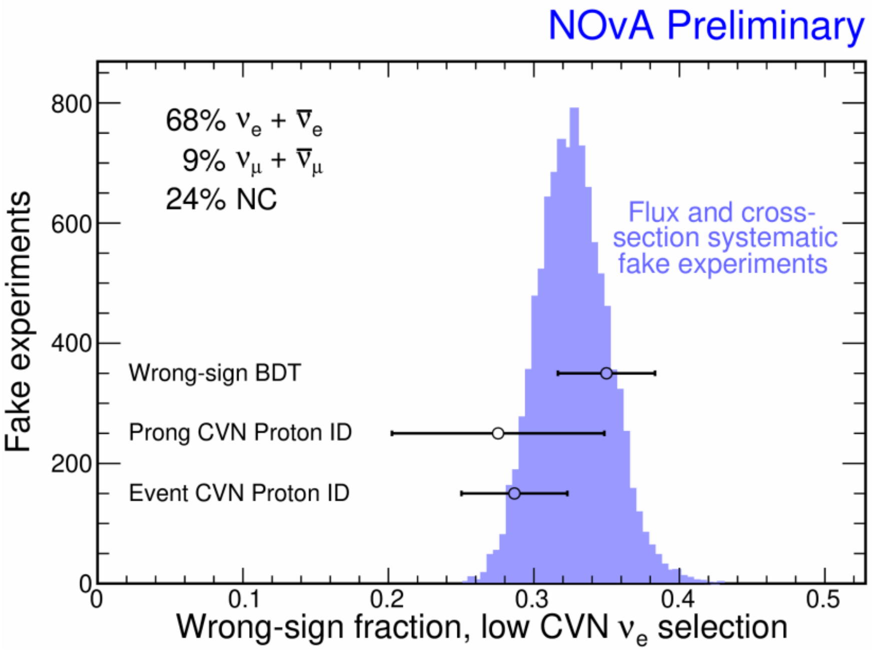
Backup Slides

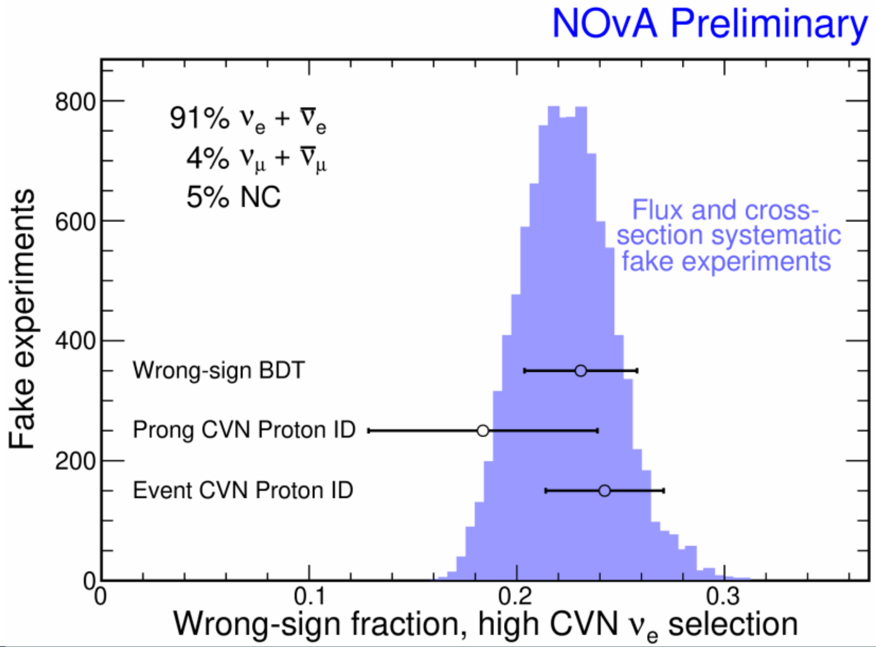
FD Efficiencies and Purities

	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%

Wrong-Sign Cross-Checks

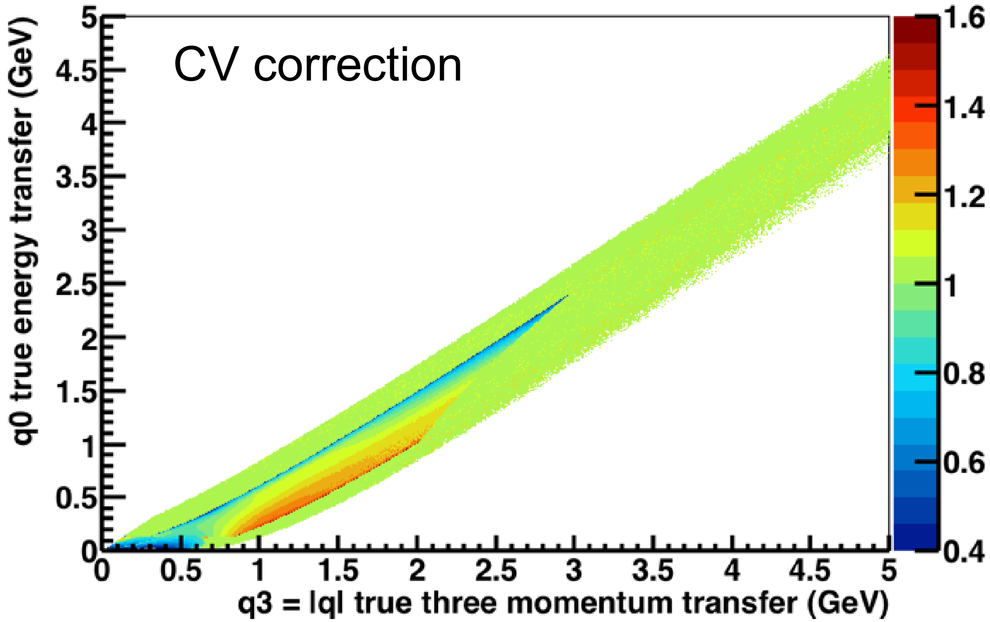


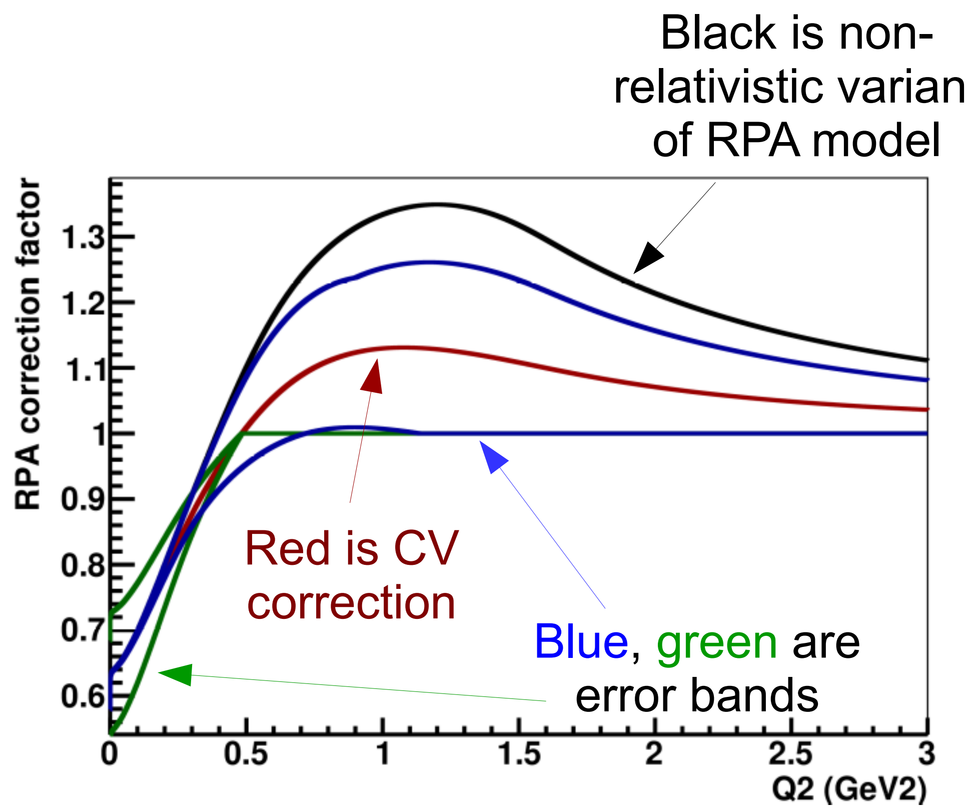




Modeling the nucleus: collective effects (RPA)

[R. Gran, arXiv:1705.02932;]



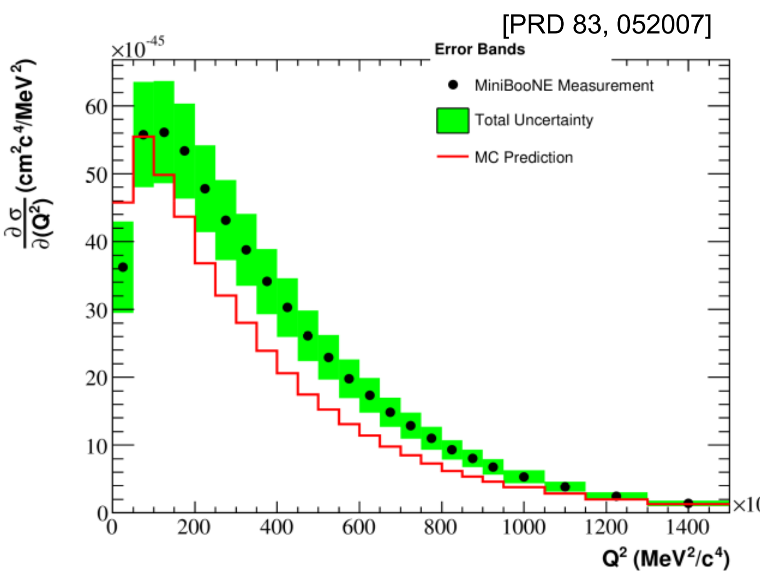


Rik Gran's work (originally for MINERvA) to extend the València RPA CCQE effect (PRC 70, 055503) to a correction for GENIE's central value and his work to extend the uncertainties in the model to higher energies (PLB 638, 325, PRD 88, 113007) naturally work reasonably well for NOvA

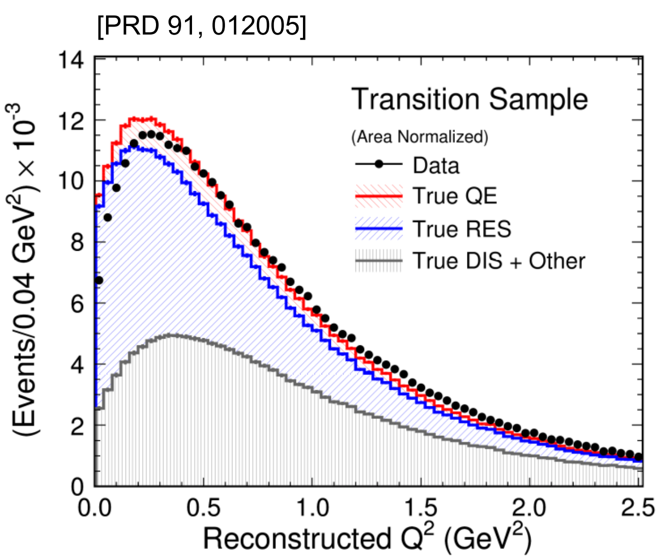
→ we apply using Rik's code

Modeling the nucleus: collective effects (RPA)

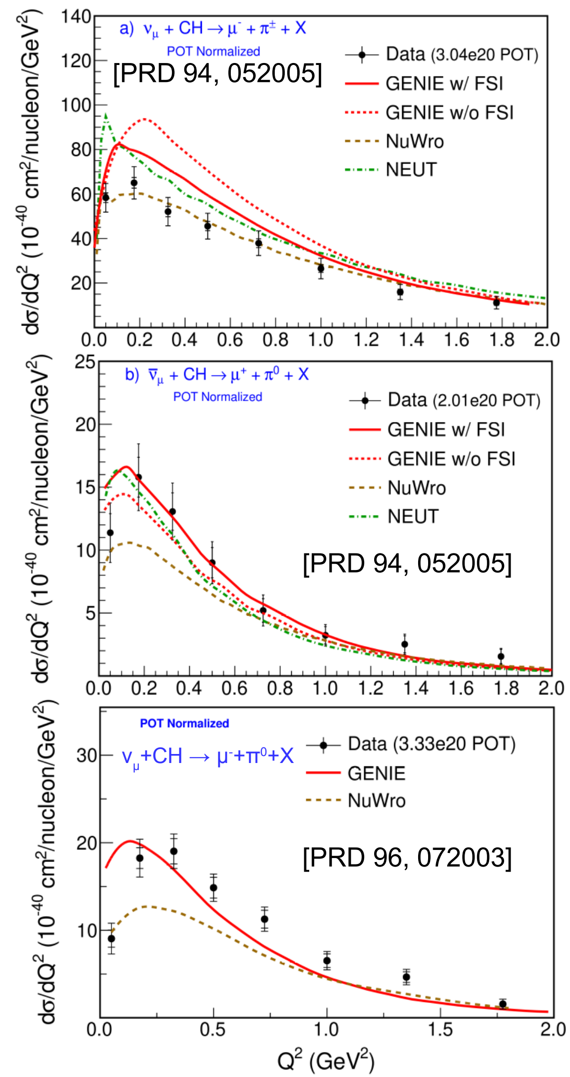
- Should Δ **production also be affected?**
  - **Energy transfers are large (>100 MeV), so perhaps not "traditional" RPA…**
  - **But suppression at low Q^2 appears in many data sets: MiniBooNE, MINOS, MINERvA**



MiniBooNE 1π+



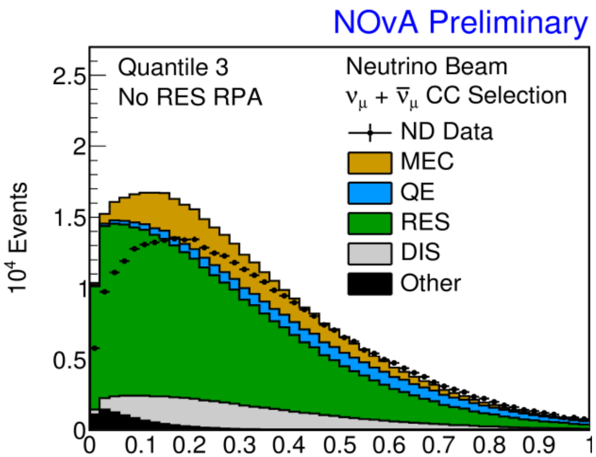
Sideband, MINOS QE

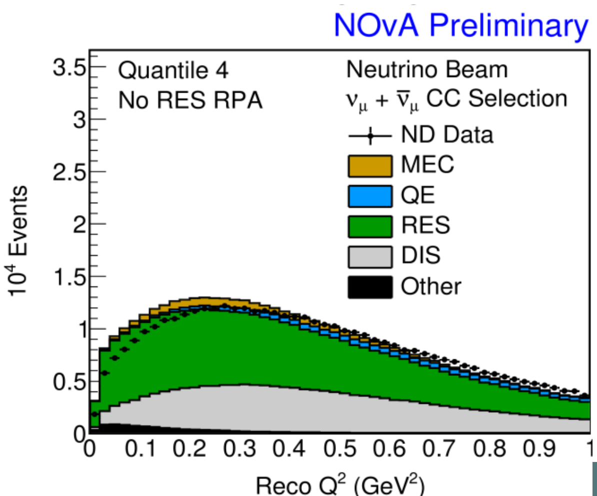


MINERvA

Modeling the nucleus: collective effects (RPA)

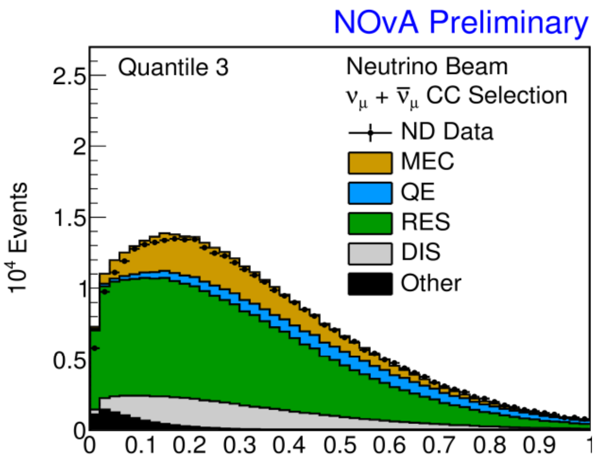
- Should Δ **production also be affected?**
  - **Not surprising that *some* initial-state nuclear effects might influence resonances (relative to RFG)...**

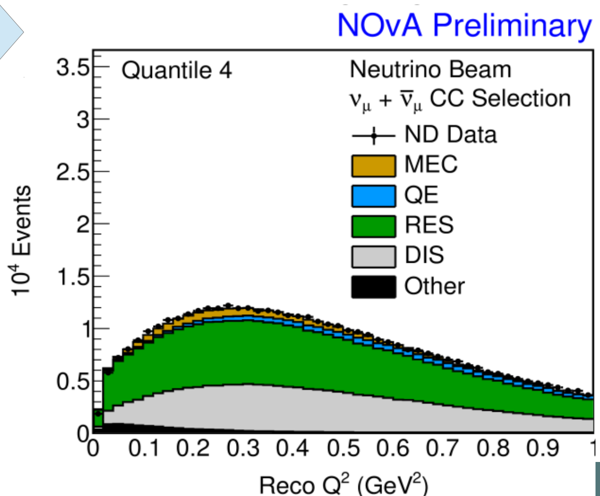




"Quantiles" are divided by hadronic energy fraction: reco E_{had}/reco E_ν.

Quantiles 3 & 4 are RES-rich regions of ν_μ candidate sample.



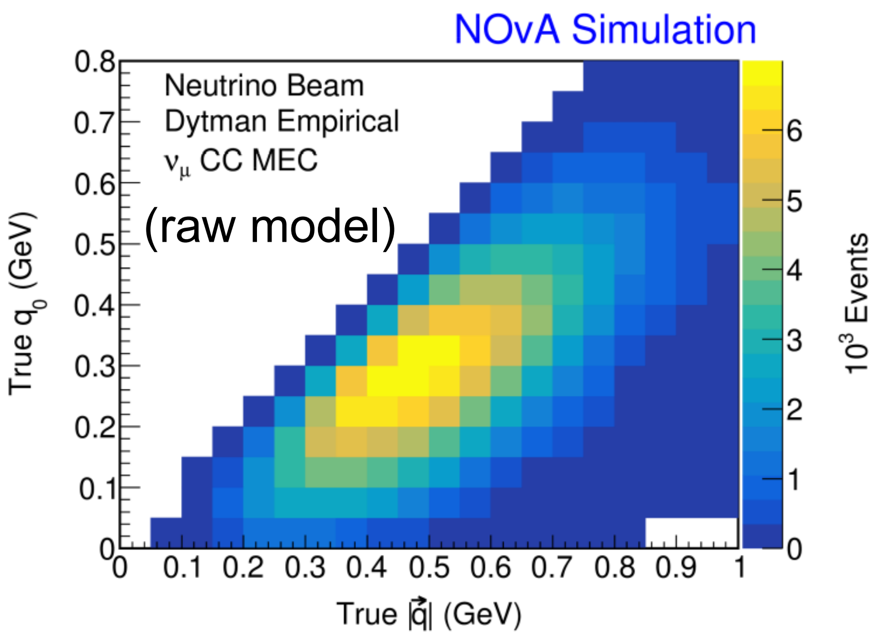


We apply the Q^2-based RPA weight from QE to resonant production as a stand-in for whatever nuclear effect it may be (w/ unmodified version as uncertainty variation)

Modeling the nucleus: tuning 2p2h-MEC

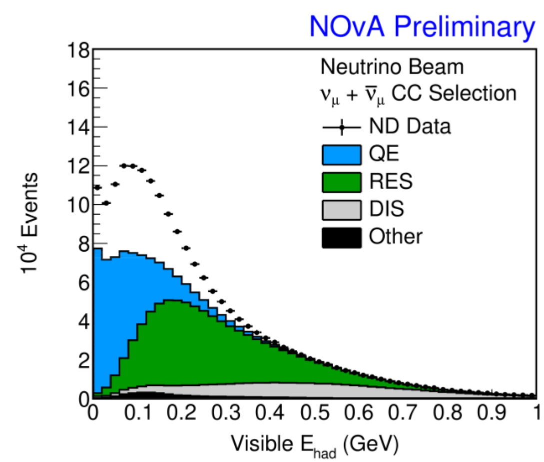
Our tuning is done in a two-dimensional space of the four-momentum transfer variables:

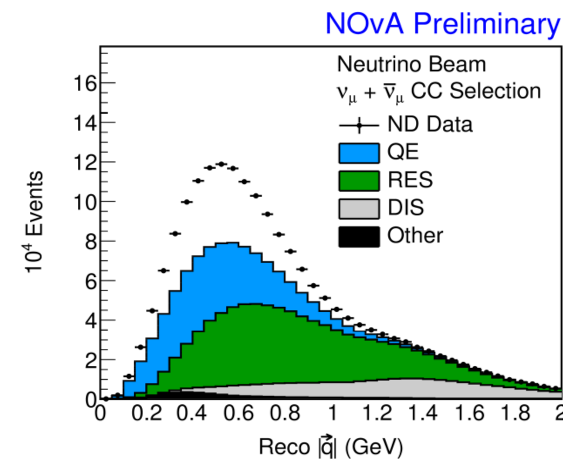
energy transfer q_0
and
momentum transfer |q|

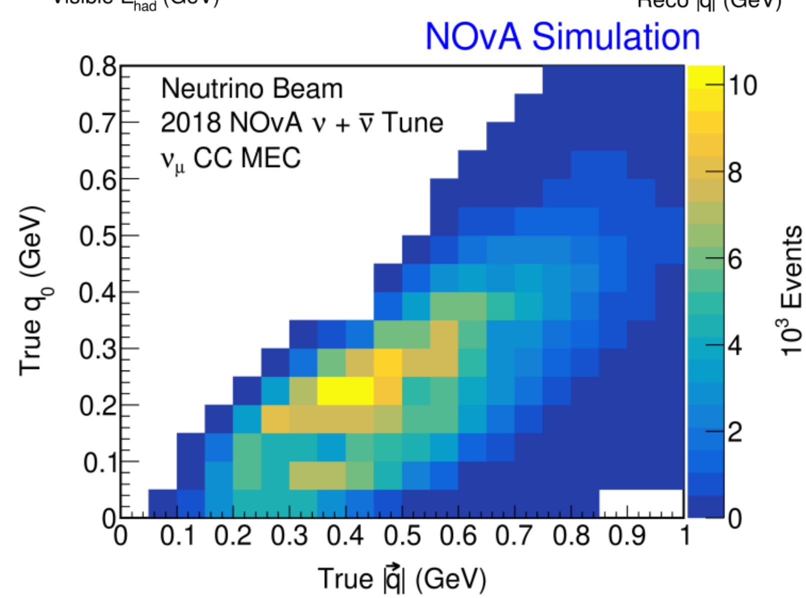


fit a weight factor for each cell in this plot

Fit in 2D space of nearest observables:
Visible E_{had} (~q_0) and reco |**q**|

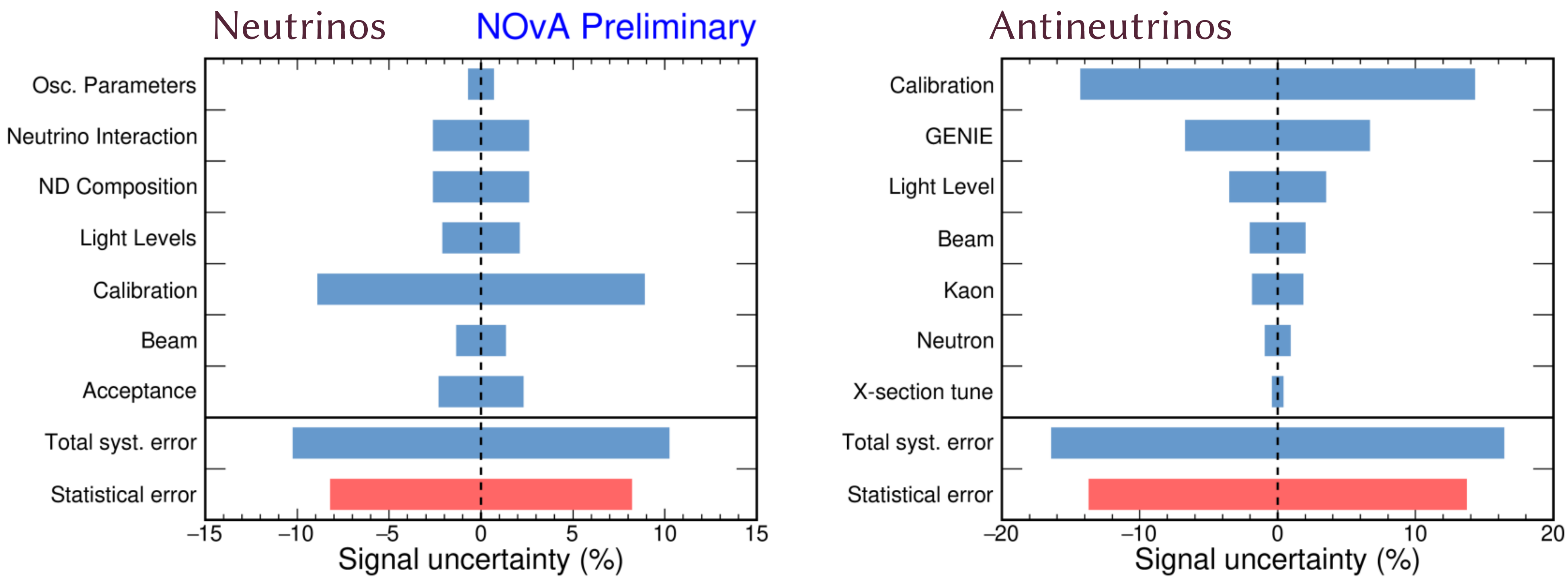






Resulting MEC shape

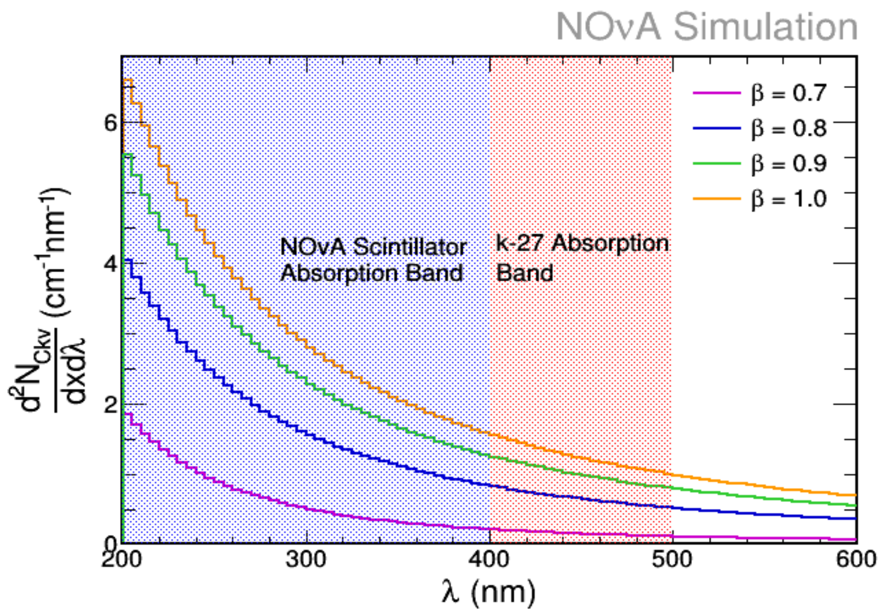
NC Systematics

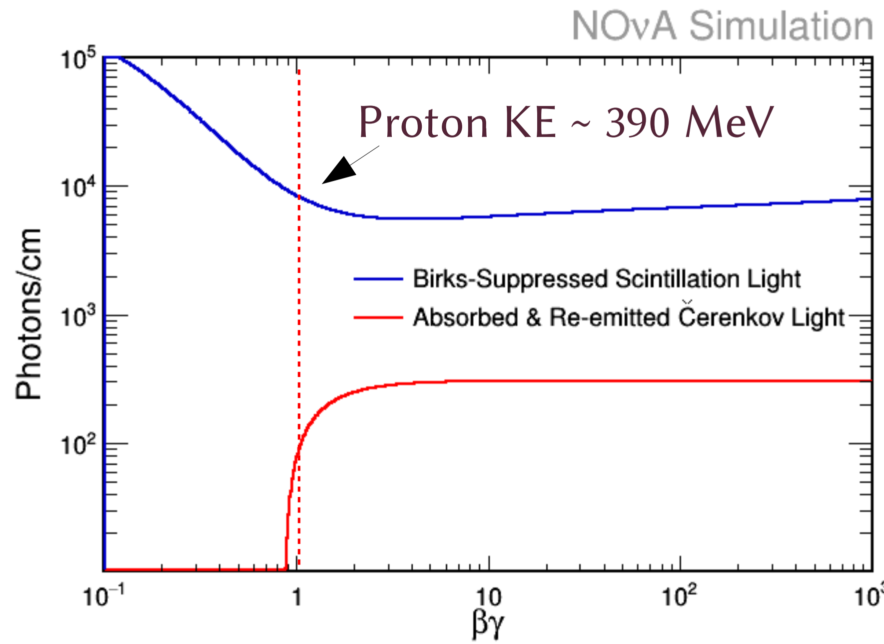


- NC events consist of an out-going neutrino and a hadronic recoil system
- Visible energy deposited is measured calorimetrically, resulting in a large calibration systematic uncertainty
- Measuring the absolute detector response for pions in the upcoming test beam program will significantly improve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

Improvements to Detector Response Modeling

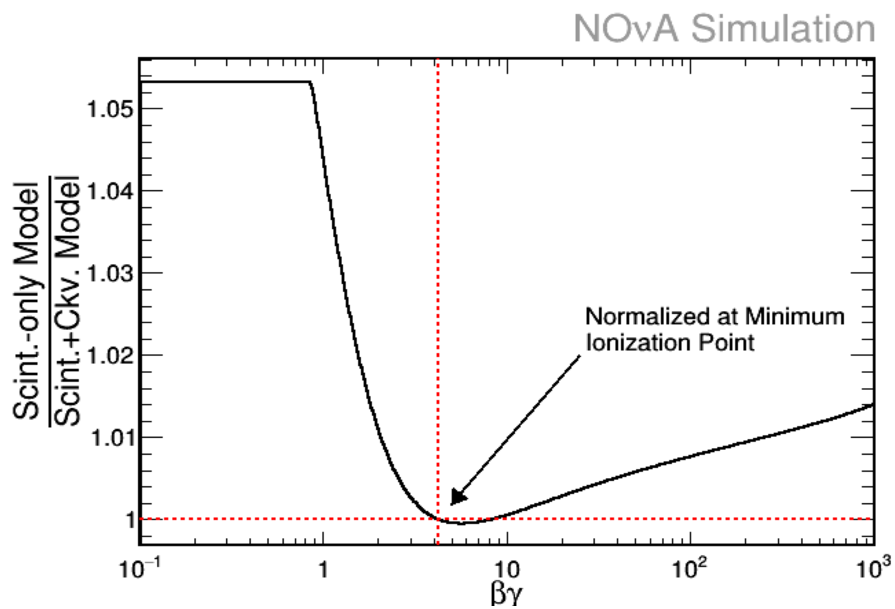
- In scintillation-based experiments, Cerenkov light is often neglected
- Scintillation yields are very large compared to Cerenkov light yields
- Most Cerenkov light is produced at short wavelengths that cannot be absorbed by the NOvA
- However, short wavelength light can be absorbed by the pseudocumene, PPO, and bis-MSB in scintillator
- Absorbed and re-emitted Cerenkov light is a small but important signal that is particularly important for the modeling of the detector response to hadronic activity

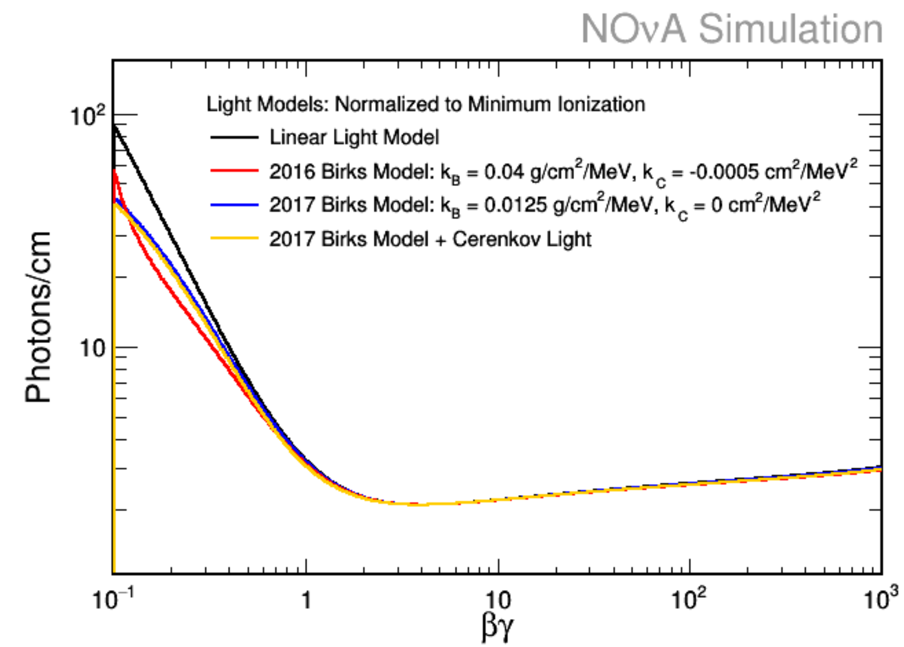




Improvements to Detector Response Modeling

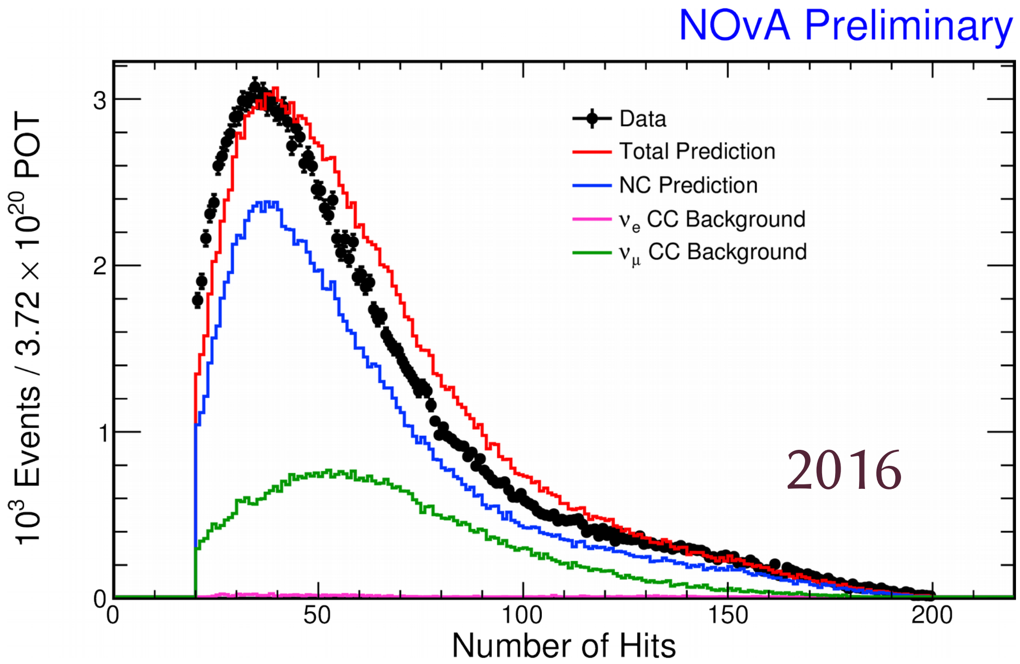
- The detector energy response is calibrated using the energy deposited by stopping cosmic muons at their minimum ionization point
- Failing to account for Cerenkov light biases the calibration of slow particles by ~ 5%
- In previous analyses, the resulting hadronic data/MC disagreement was minimized by tuning scintillator quenching, requiring significant systematic uncertainties

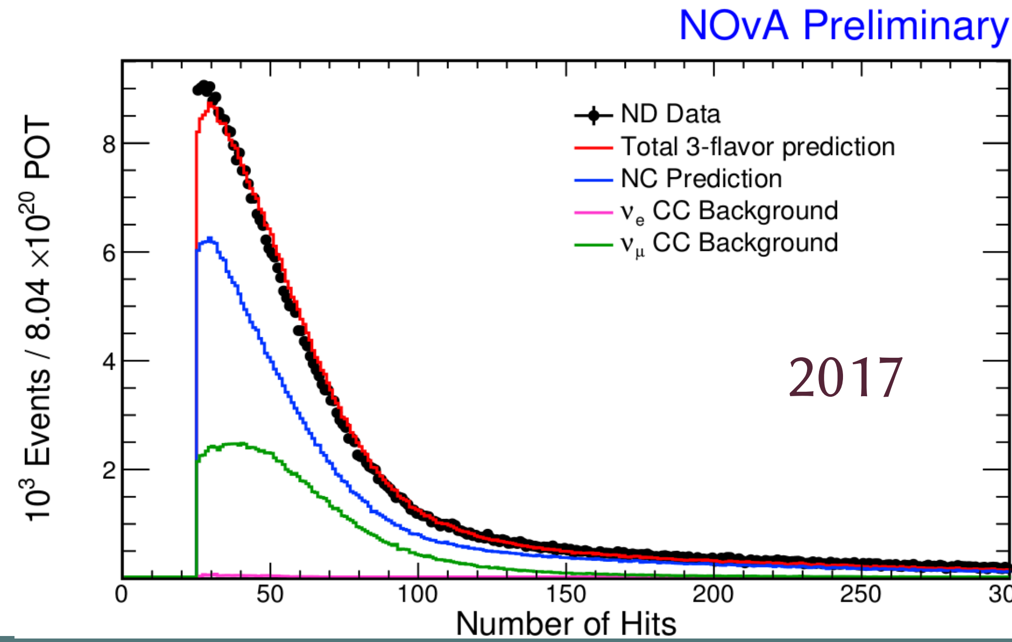




Improvements to Detector Response Modeling

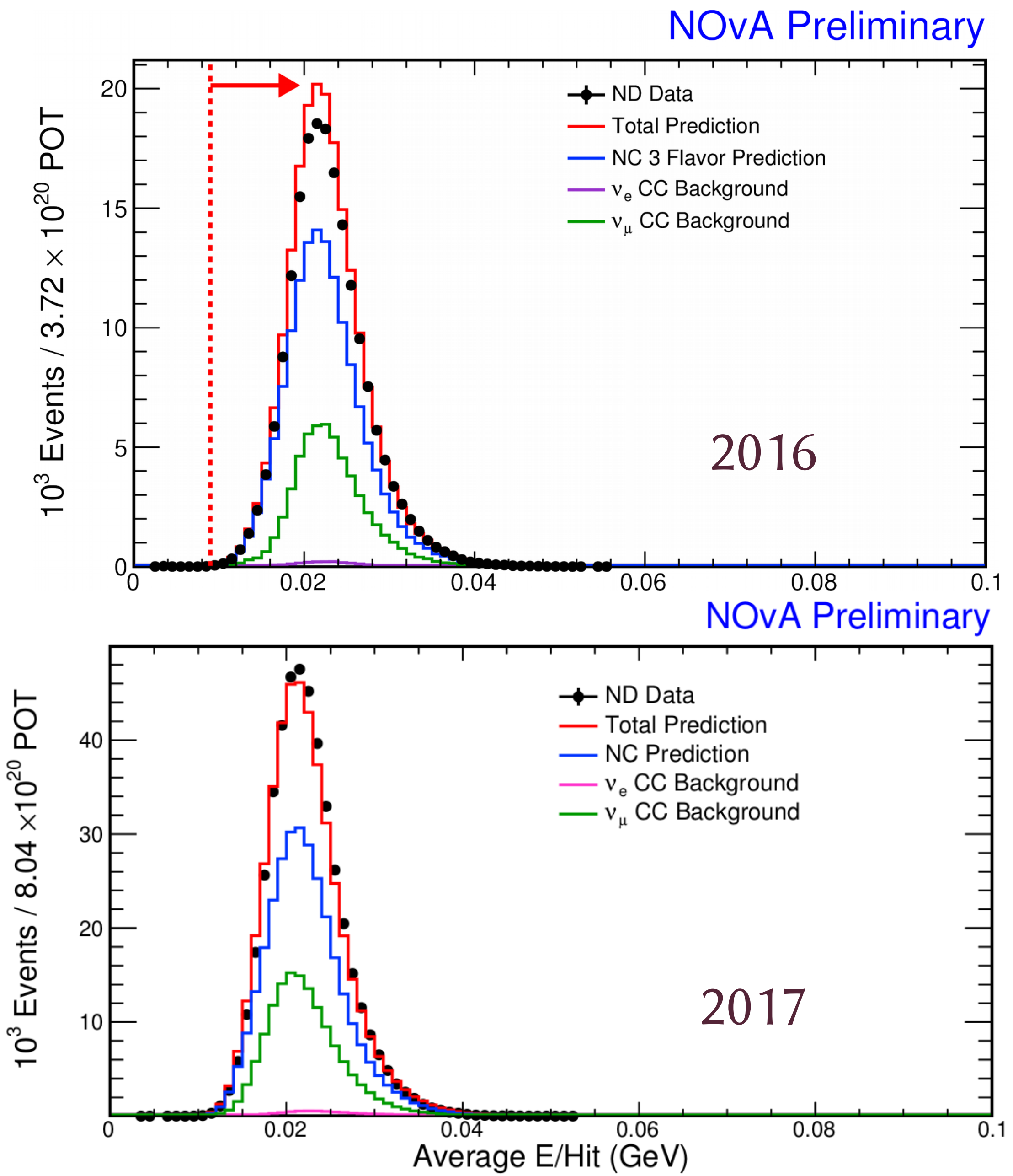
- Modeling the absorption and re-emission of Cerenkov light produced significant improvements in data/MC agreement, especially for:
  - Number of hits
  - Energy/hit
- Allows for a reduction in systematic uncertainties





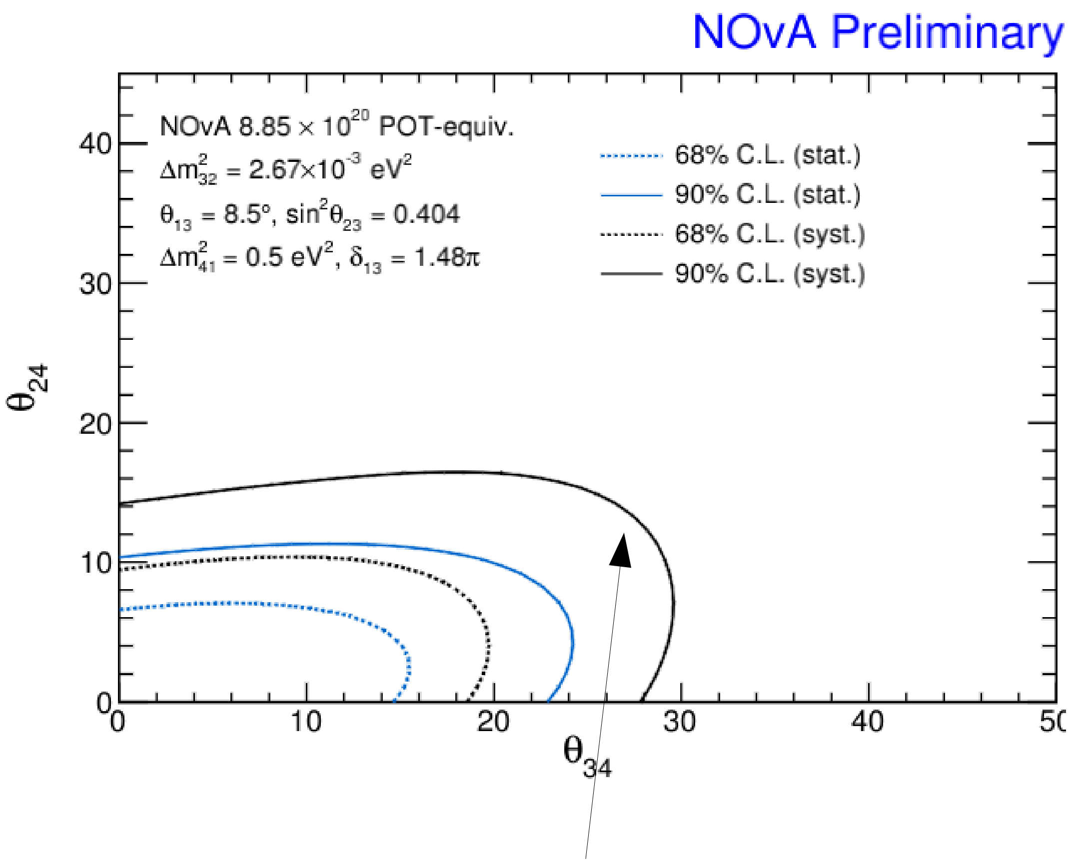
Improvements to Detector Response Modeling

- In previous analyses, the scintillator non-linearity was tuned to minimize the data/MC disagreement energy lost by protons
- Recently, Cerenkov light was uncovered as an extra source of scintillator non-linearity
  - Short-wavelength Cerenkov light can be absorbed and re-emitted by the scintillator at detectable wavelengths
- Modeling this process produced significant improvements in data/MC agreement, especially for:
  - Energy/hit
  - Number of hits



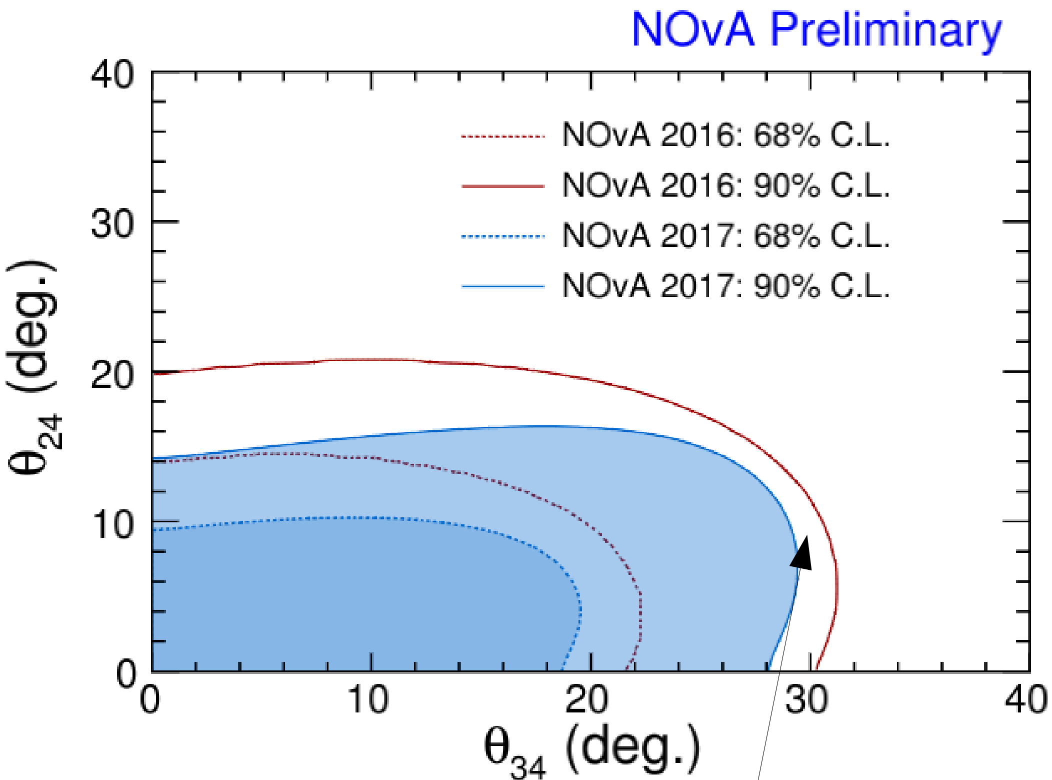
Shape Fit: 2D 90% C.L. Limits

- Constrain θ_{23}, Δm^2_{32}, and δ_{13} to NOvA's degenerate best fit points
  - Fit separately for each three-flavor degenerate solution and take the least constraining result
- Solar and reactor data constrains $\sin^2\theta_{14} < 0.041$
  - Assume $\theta_{14} = 0$ and $\delta_{14} = 0$
- Profile over $\theta_{23,}$, Δm^2_{32}, δ_{24}
- Limit Δm^2_{41}:
  - $0.05\ \text{eV}^2 < \Delta m^2_{41} < 0.5\ \text{eV}^2$
  - No significant ND oscillations
  - Rapid oscillations in FD
- Perform a shape-based fit for θ_{24} and θ_{34}



Stretching at large θ_{24} and θ_{34} is due to profiling over δ_{24}

Shape Fit: 2D 90% C.L. Limits



2016 analysis was a rate only analysis

	θ_{24}	θ_{34}	$\|U_{\mu 4}\|^2$	$\|U_{\tau 4}\|^2$
NOvA 2016	20.8°	31.2°	0.126	0.268
NOvA 2017	16.2°	29.8°	0.078	0.228
MINOS	7.3°	26.6°	0.016	0.20
SuperK	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15

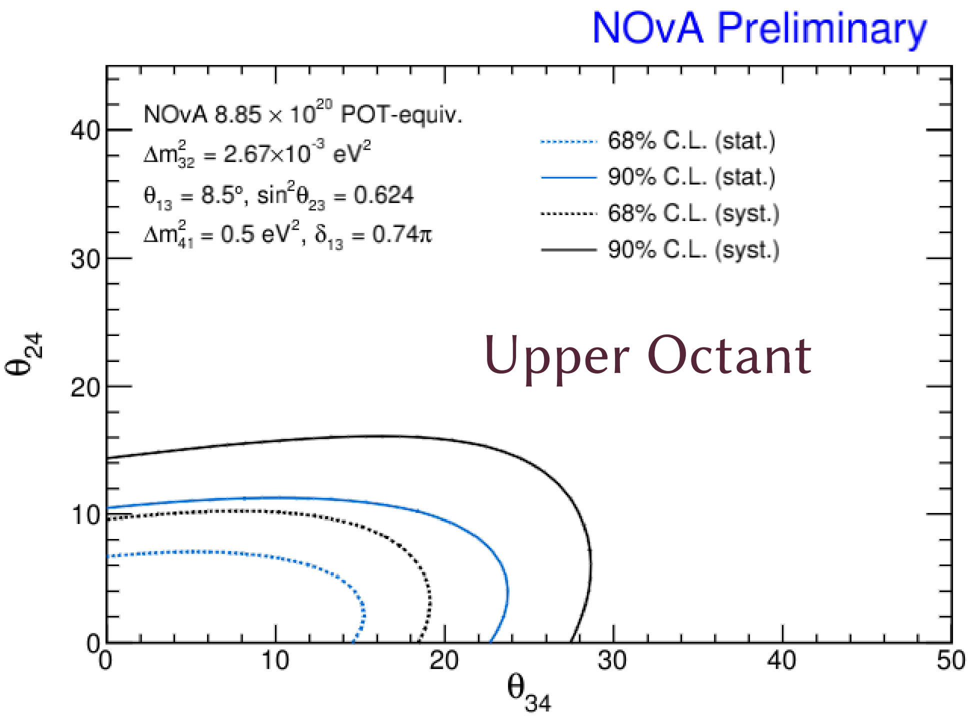
Fit in the lower octant is the least constraining

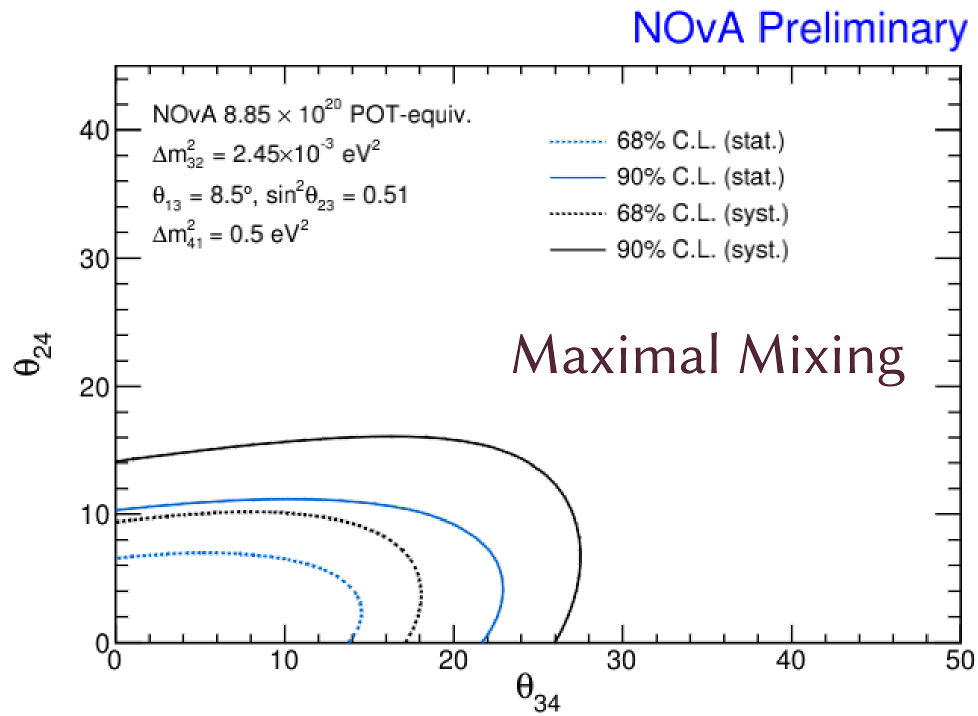
NOvA 2017 analysis improves over the NOvA 2016 limit

→ θ_{24} by 4.6°

→ θ_{34} by 1.4°

2D Limits


NOvA Preliminary
NOvA 8.85 × 10^20 POT-equiv.
Δm²₃₂ = 2.67×10⁻³ eV²
θ₁₃ = 8.5°, sin²θ₂₃ = 0.624
Δm²₄₁ = 0.5 eV², δ₁₃ = 0.74π
68% C.L. (stat.)
90% C.L. (stat.)
68% C.L. (syst.)
90% C.L. (syst.)
Upper Octant
θ24
θ34


NOvA Preliminary
NOvA 8.85 × 10^20 POT-equiv.
Δm²₃₂ = 2.45×10⁻³ eV²
θ₁₃ = 8.5°, sin²θ₂₃ = 0.51
Δm²₄₁ = 0.5 eV²
68% C.L. (stat.)
90% C.L. (stat.)
68% C.L. (syst.)
90% C.L. (syst.)
Maximal Mixing
θ24
θ34

Convolutional Neural Networks

- Deep learning is a new paradigm that has caused a renaissance in the machine learning community.
  - Made possible by better activation functions, better weight initialization, and the advent of cheap GPUs.
- One variant – the convolutional neural network has been highly successful at image recognition tasks.
- Two basic type of layers:
  - Convolutional layers – apply discrete convolutions using learned kernels to extract features from the image.
  - Pooling layers – downsample the image and increase translational invariance in the final output.
- Stacked structure of convolutional and pooling layers extract increasingly abstract features from the input raw data encoding both local and global structure.
- Relatively new:
  - LeNet – one of the first (1998)
  - AlexNet – the one that started the revolution (2012)