First NOvA Oscillation Results with Neutrino and Antineutrino Beams

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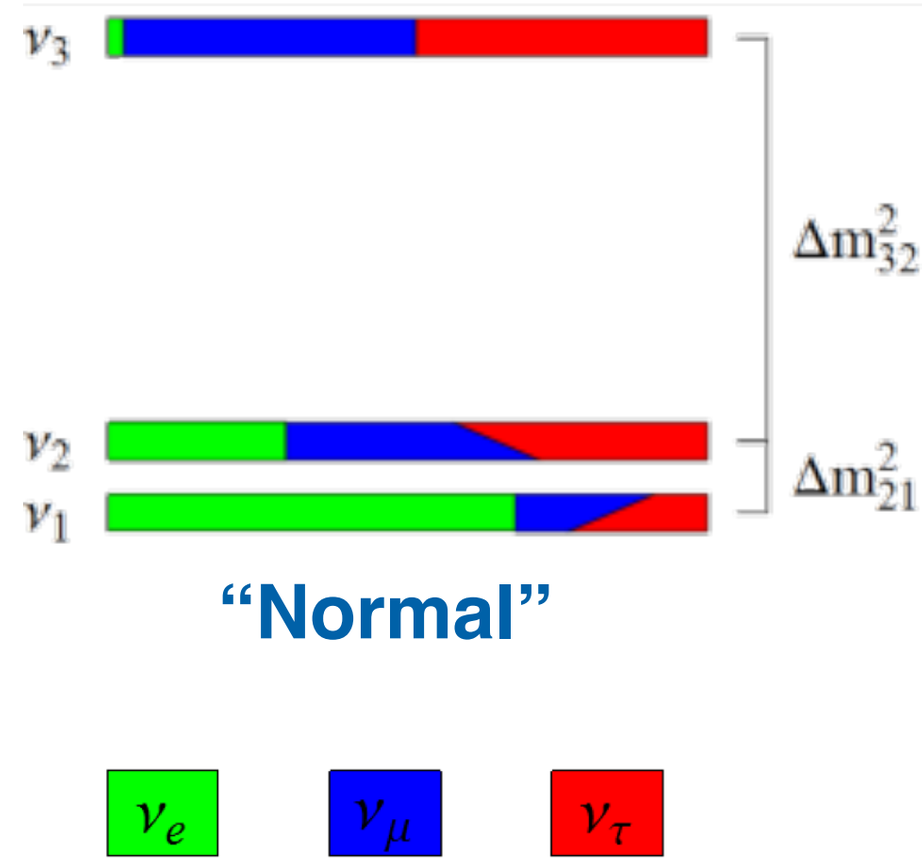
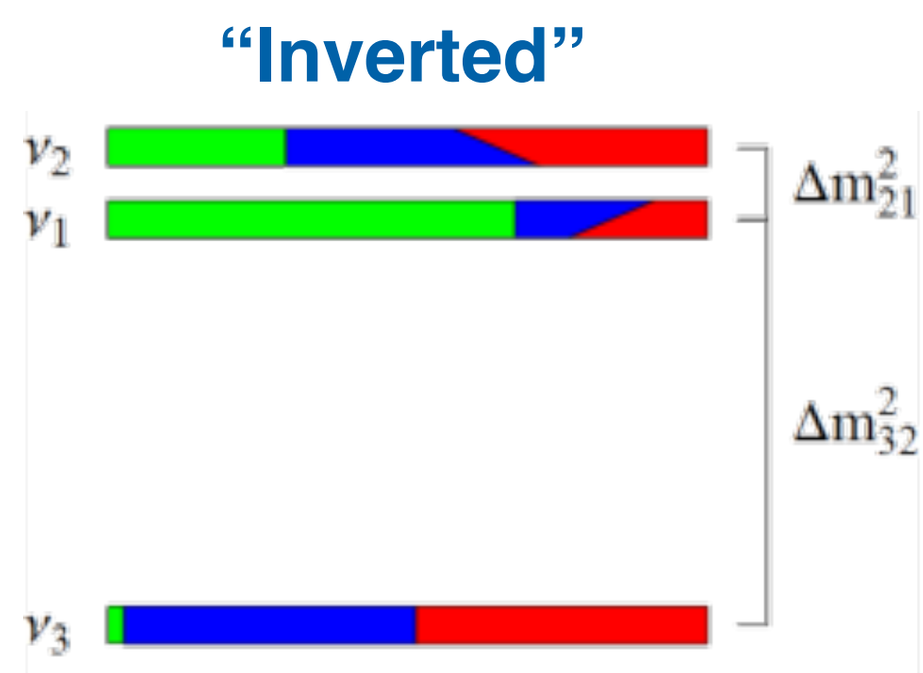
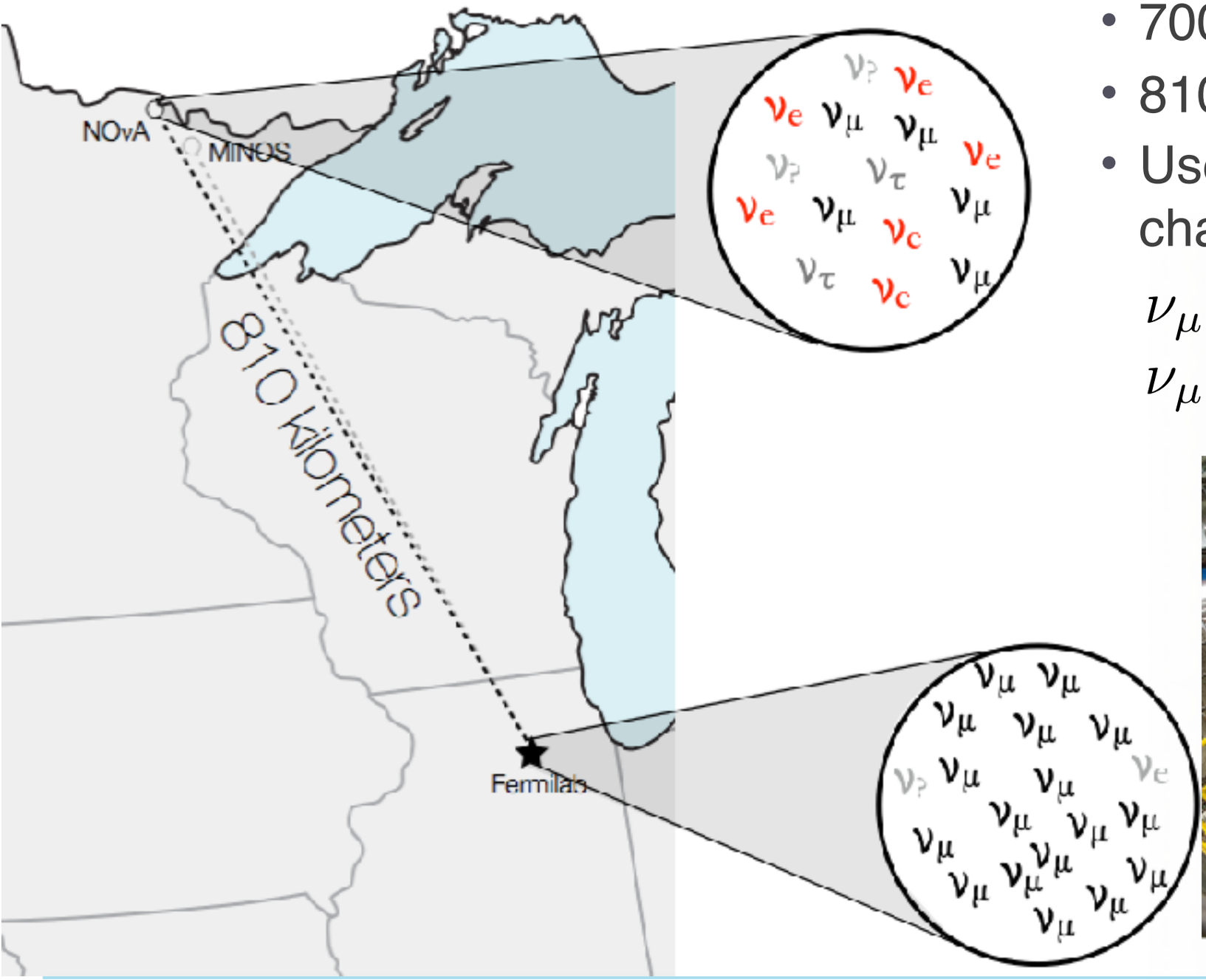
NOvA Physics Goals

- What is the neutrino mass hierarchy or ordering?
- Is the mixing angle θ_{23} maximal, if not which octant is it in?
- Is there CP violation in the lepton sector?
- Are there additional neutrinos beyond the three known active flavors?
- Also, cross section measurements, non-beam physics, and exotic searches





The NOvA Experiment



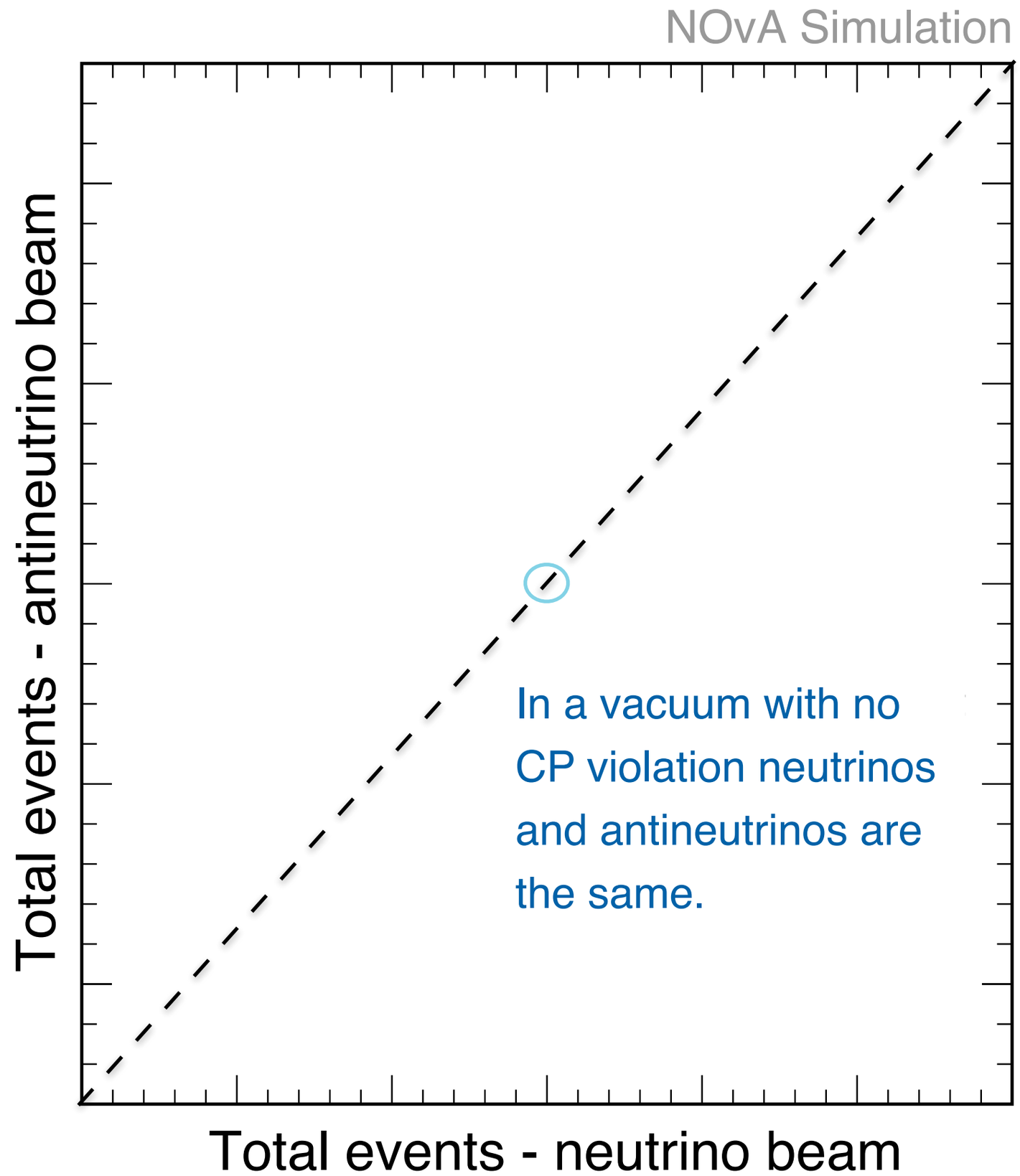
- Observe neutrinos from NuMI neutrino beam line at Fermilab
- Two functionally identical detectors, 14 milliradians off-axis from beam center
- 700 kW beam
- 810 km baseline
- Uses four primary oscillation channels:

$$\nu_\mu \rightarrow \nu_\mu \qquad \overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$$
$$\nu_\mu \rightarrow \nu_e \qquad \overline{\nu}_\mu \rightarrow \overline{\nu}_e$$

NOvA Physics Goals

Joint analysis of muon (anti)neutrino disappearance and electron (anti)neutrino appearance helps answer many unknown questions in neutrino physics.

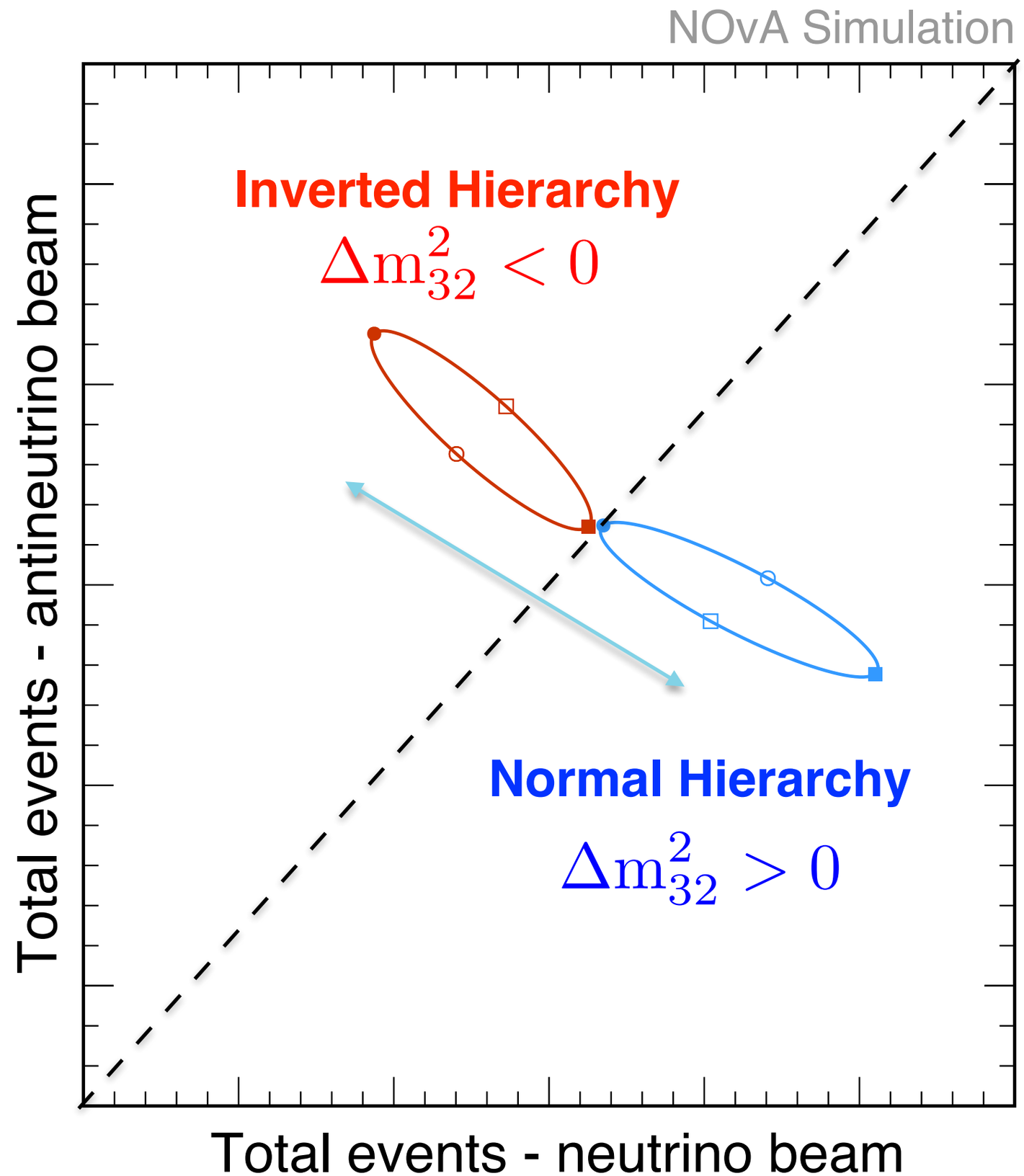
Examine effects of oscillation parameters on the number of appeared electron neutrino and antineutrino events observed.



NOvA Physics Goals

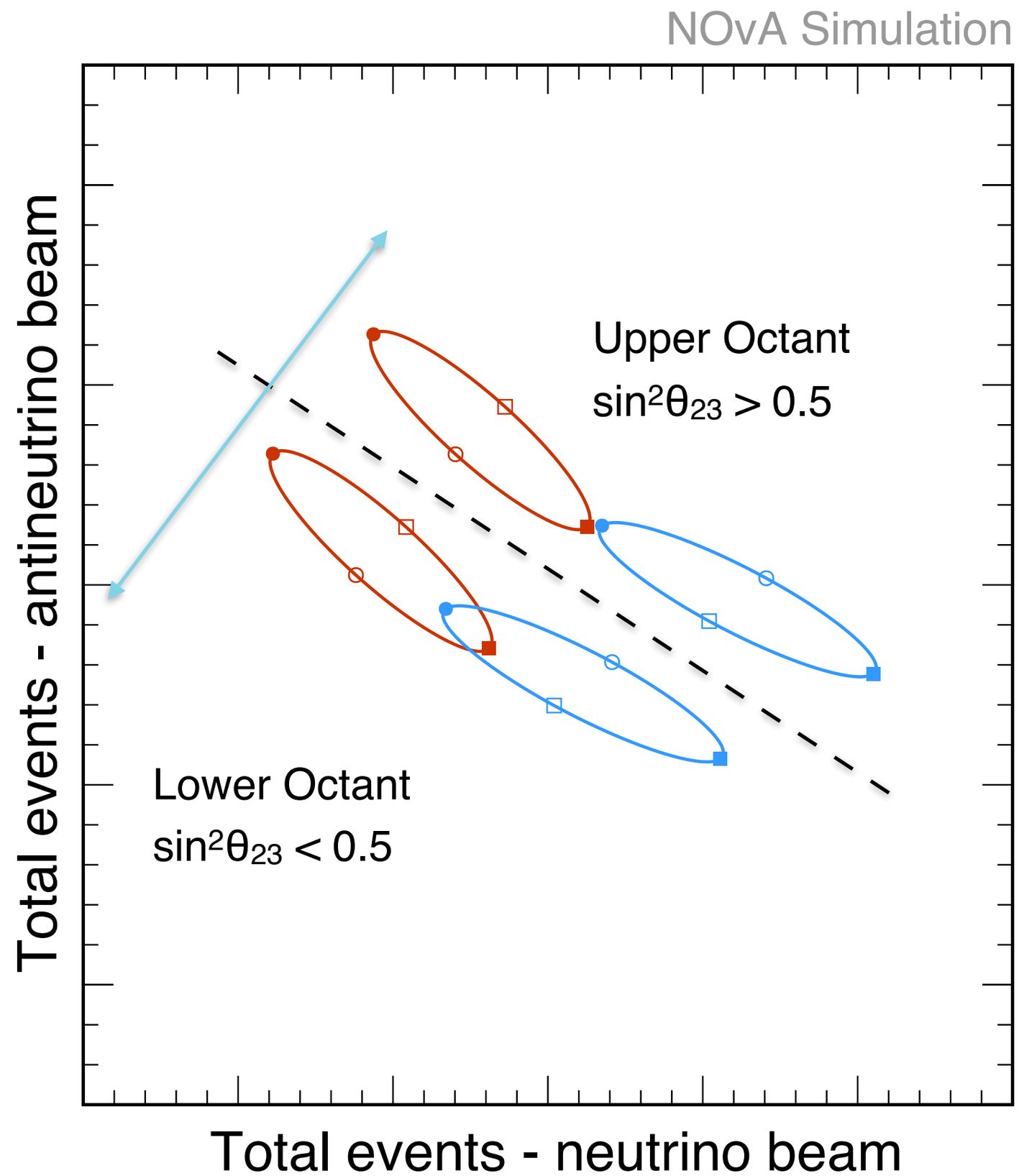
Is the neutrino mass hierarchy normal or inverted?

Matter effect alters oscillation probability for neutrinos and antineutrinos. NOvA baseline is 810 km.



NOvA Physics Goals

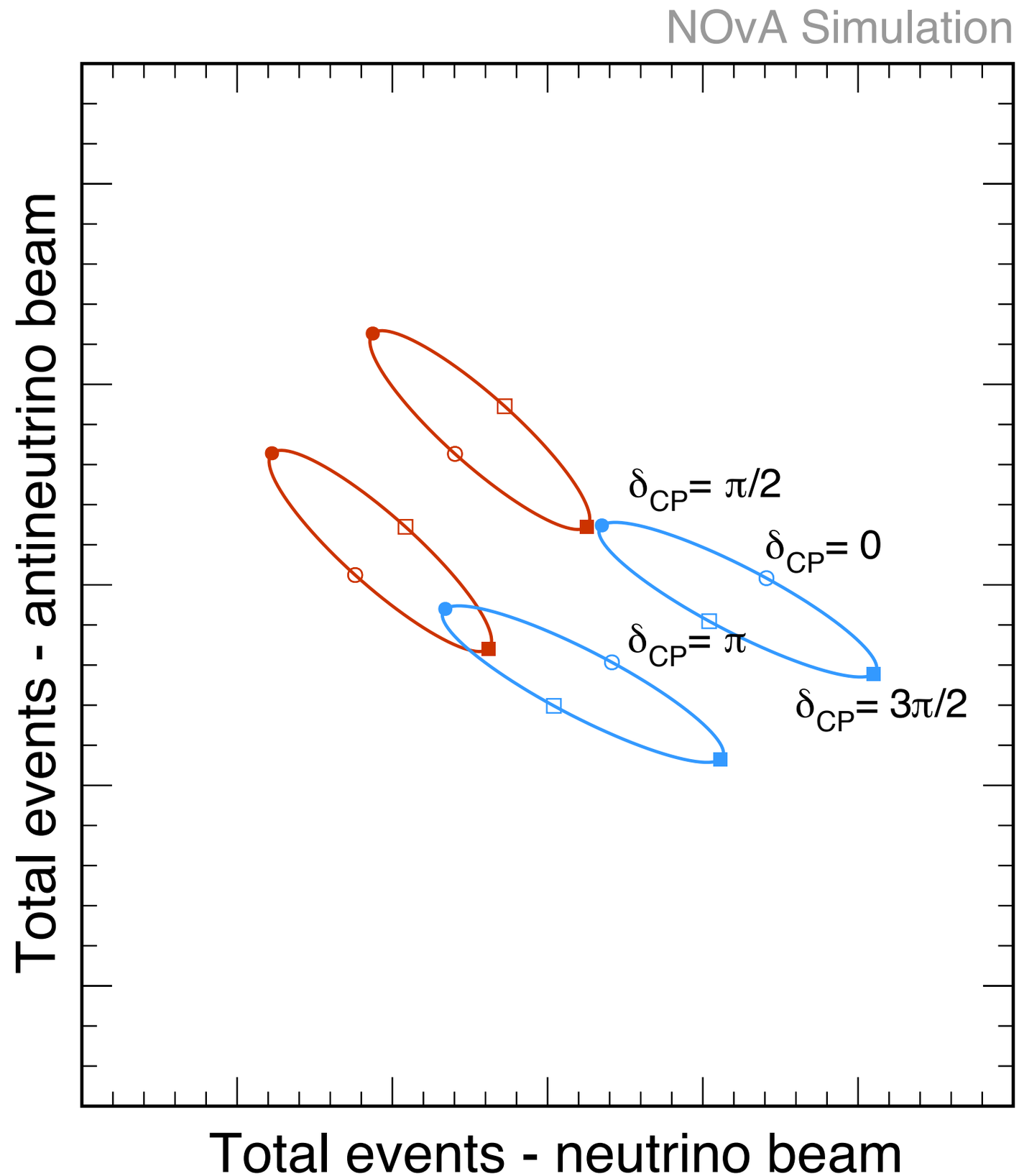
Is the large mixing angle θ_{23} maximal, if not which octant does it fall in?



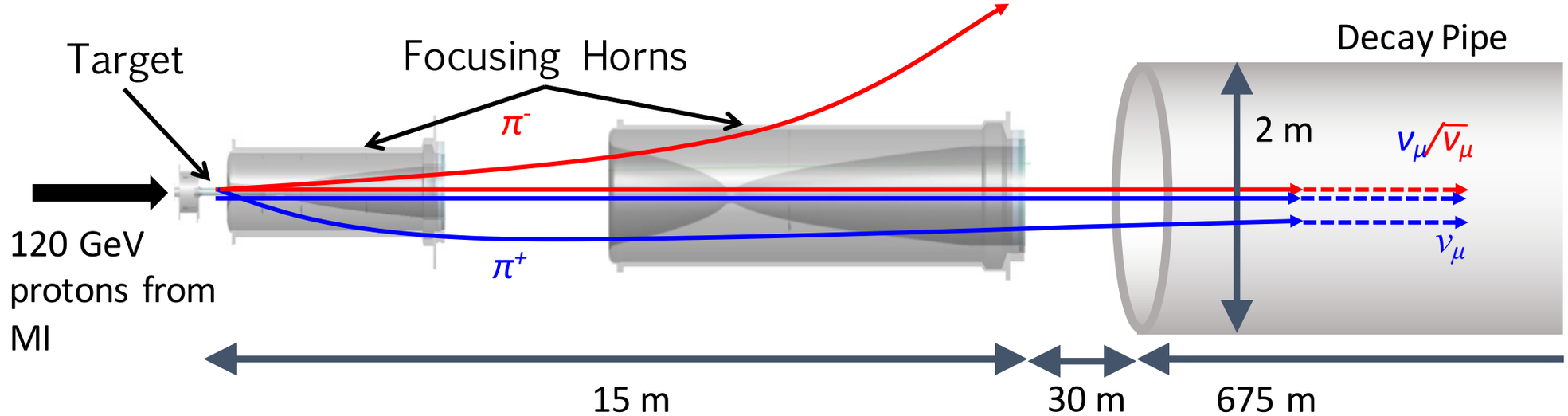
NOvA Physics Goals

Is there CP Violation in the lepton sector?

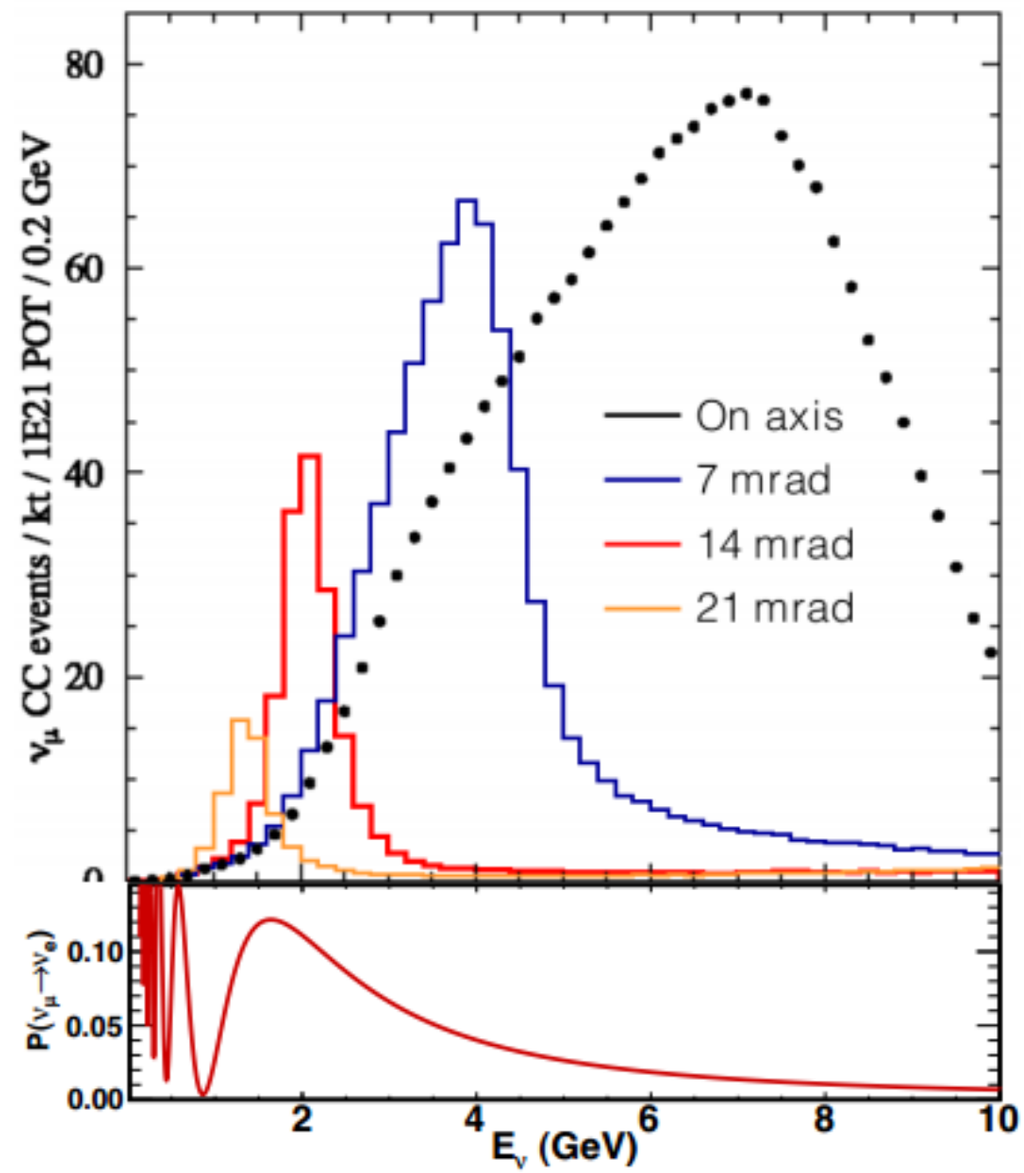
Some regions of phase space are degenerate to one or more questions.



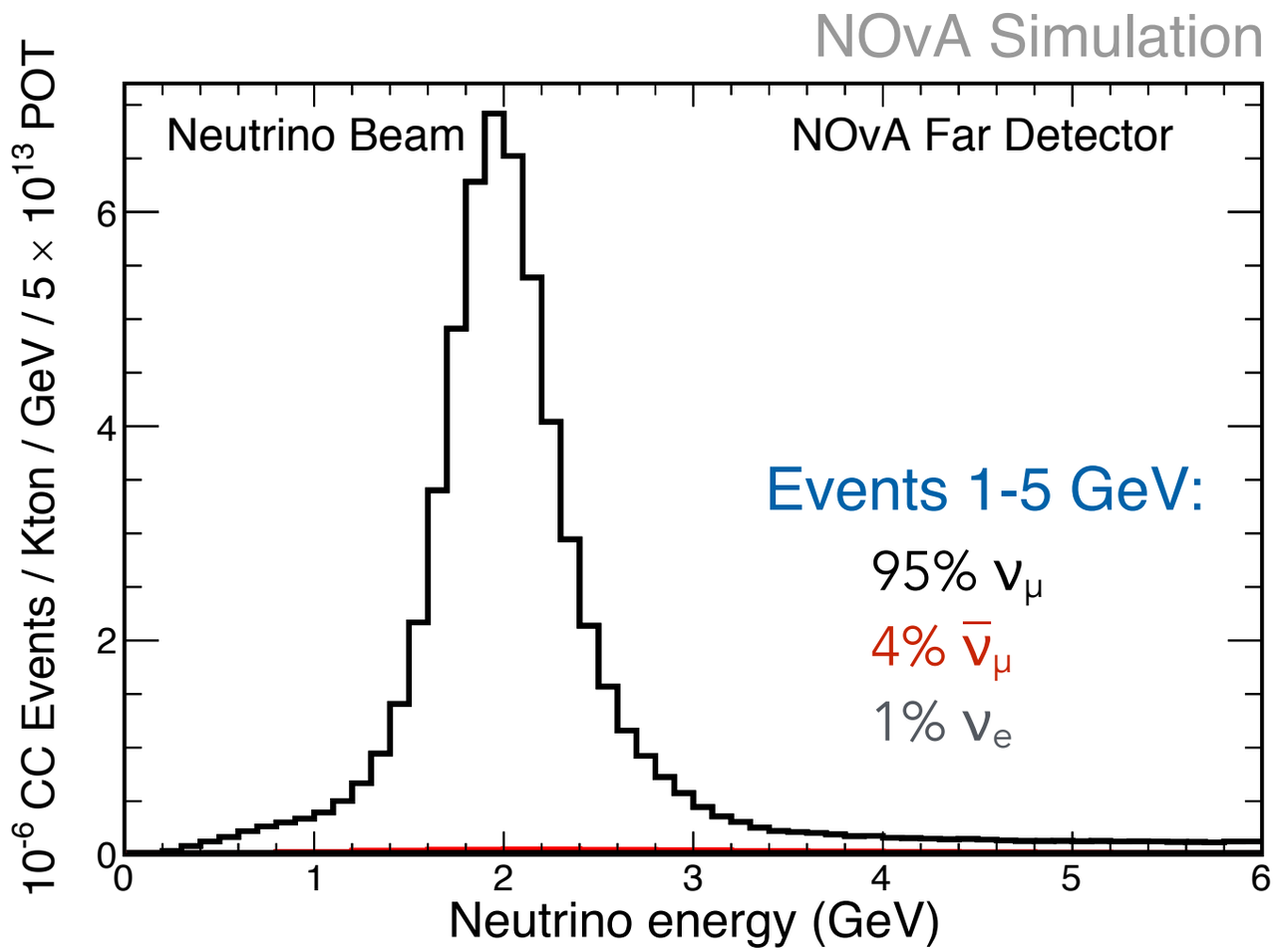
NuMI Beam

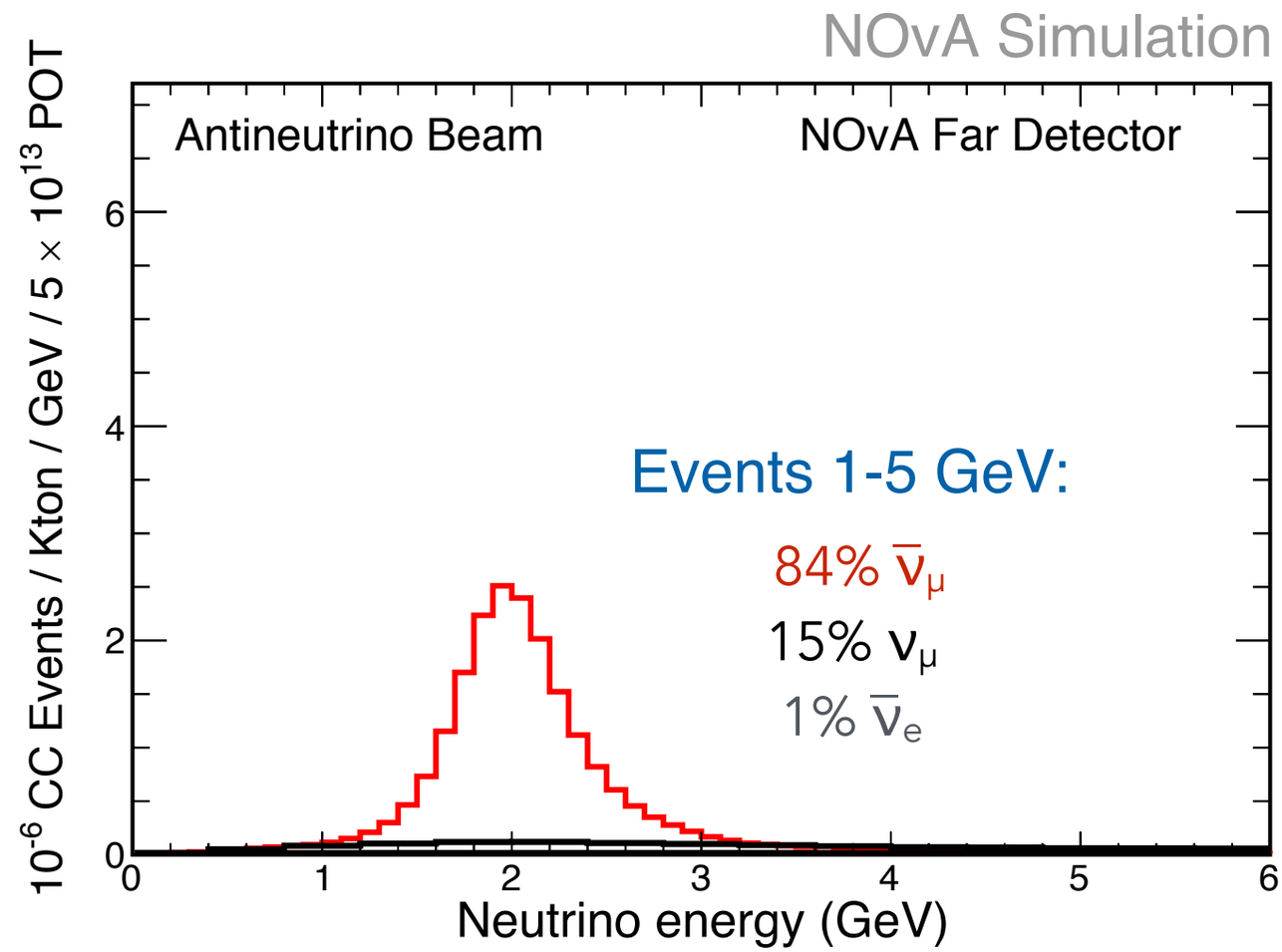


- 120 GeV protons extracted from the Main Injector at Fermilab in 10 μs spills
- Magnetic focusing horns allow selection of charge sign for selecting a neutrino or anti-neutrino beam
- 14.6 milli-radians off-axis, narrow beam around oscillation maximum



NuMI Beam

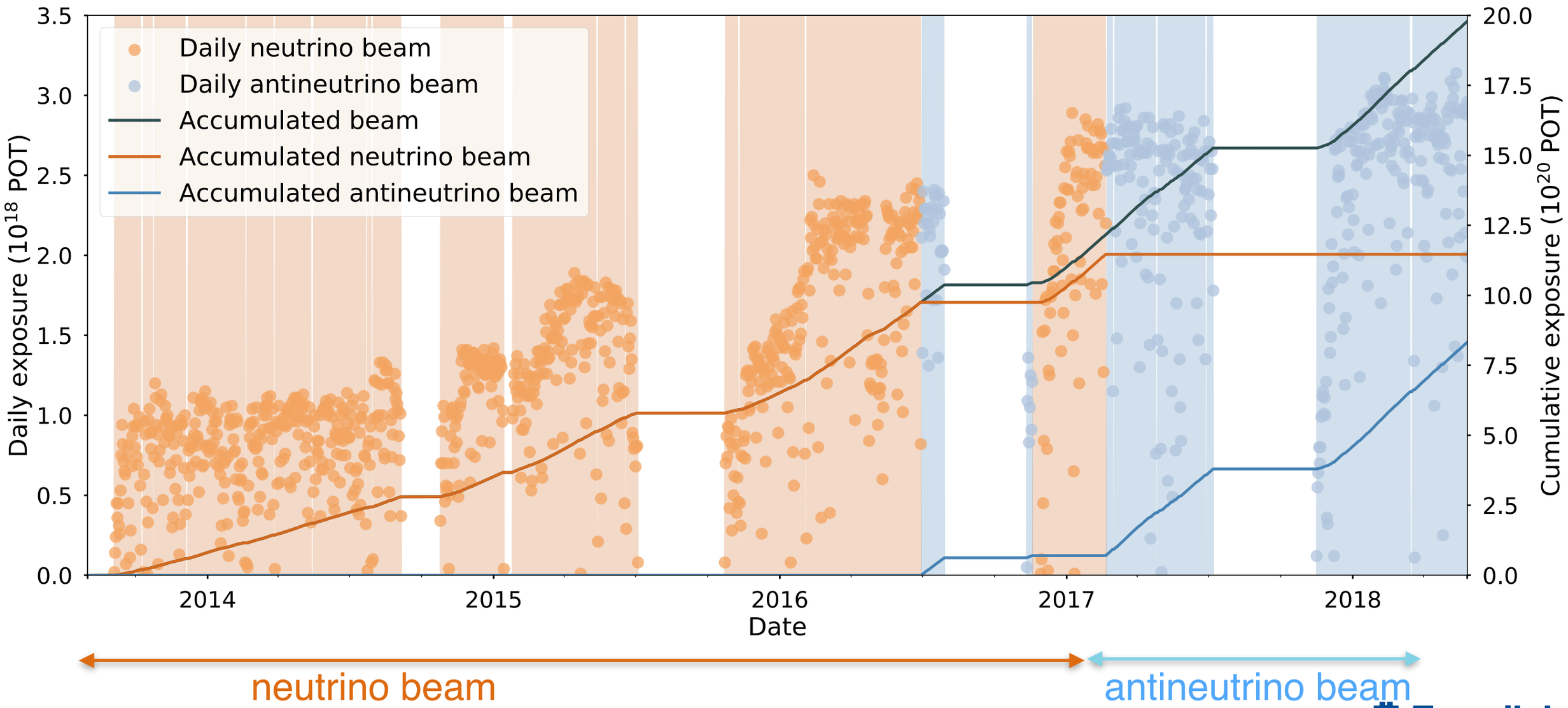




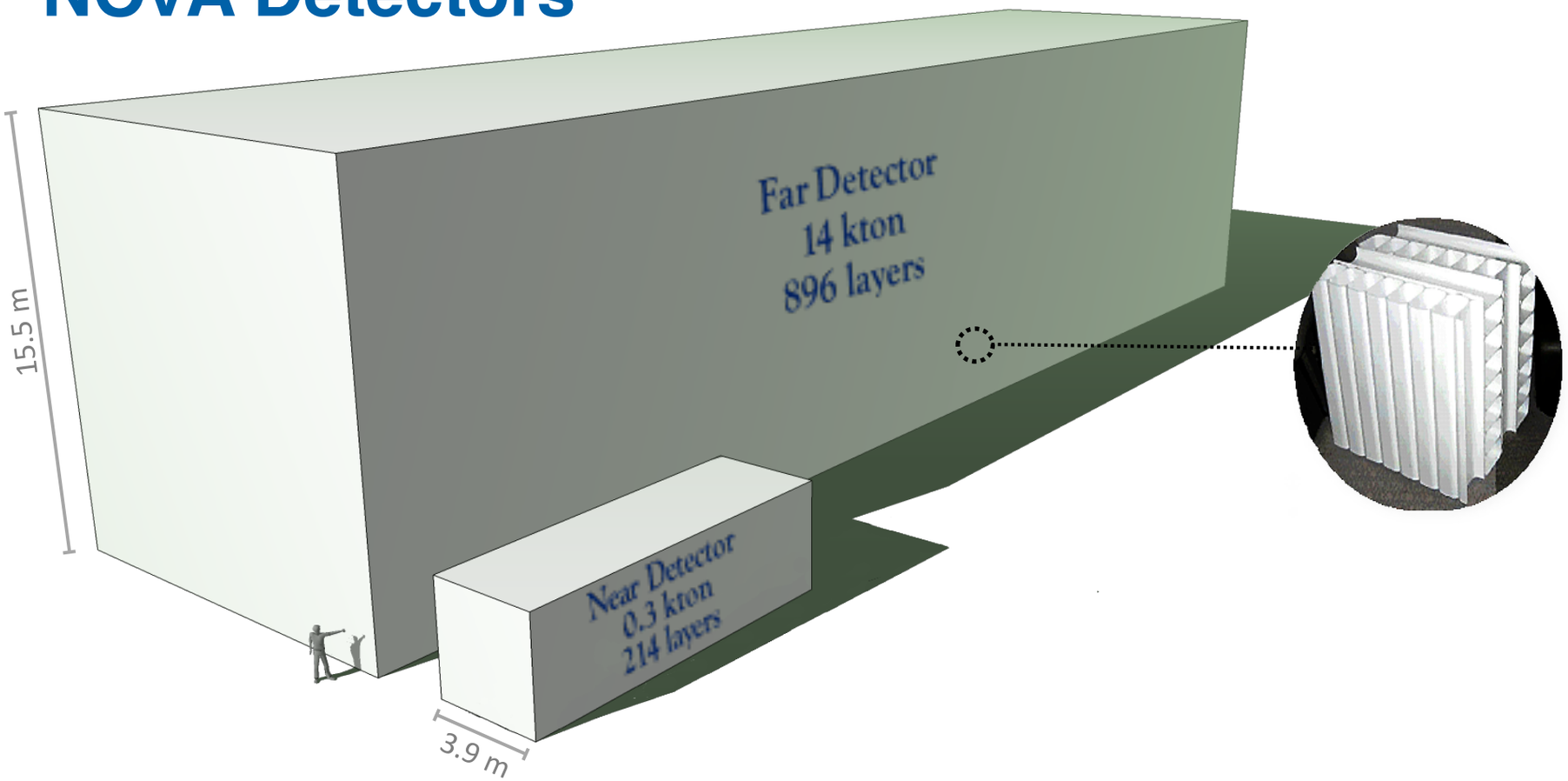
- Off-axis beam reduces contamination of wrong-sign neutrinos.
- Note the cross section is ~2.8 times lower for antineutrino interactions
- Antineutrino events typically have more energy in the lepton and less hadronic energy.

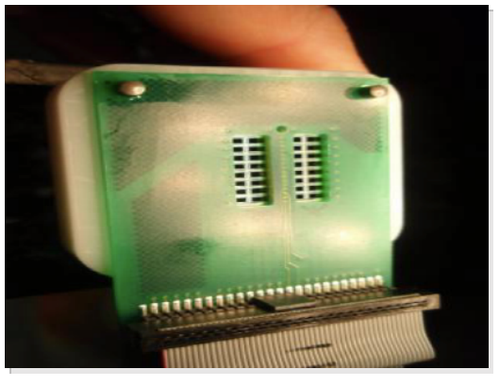
NuMI Beam Performance

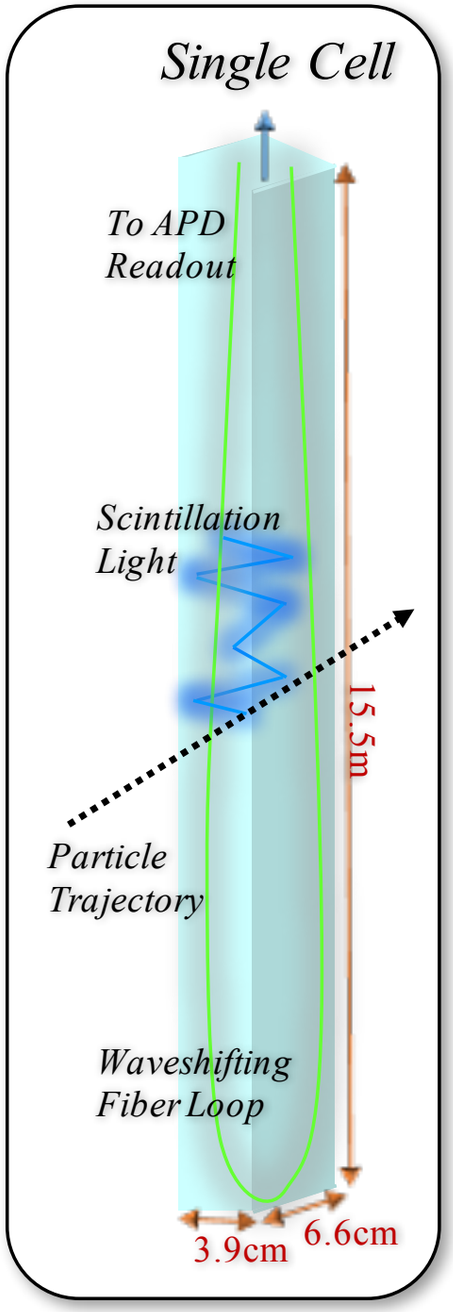
- Running at 700 kW design power since January 2017, the highest power beam in the world
- Analysis of 8.85x10^{20} protons-on-target in neutrino beam configuration
- First 6.9x10^{20} POT of antineutrino beam recorded February 2017 to April 2018



NOvA Detectors

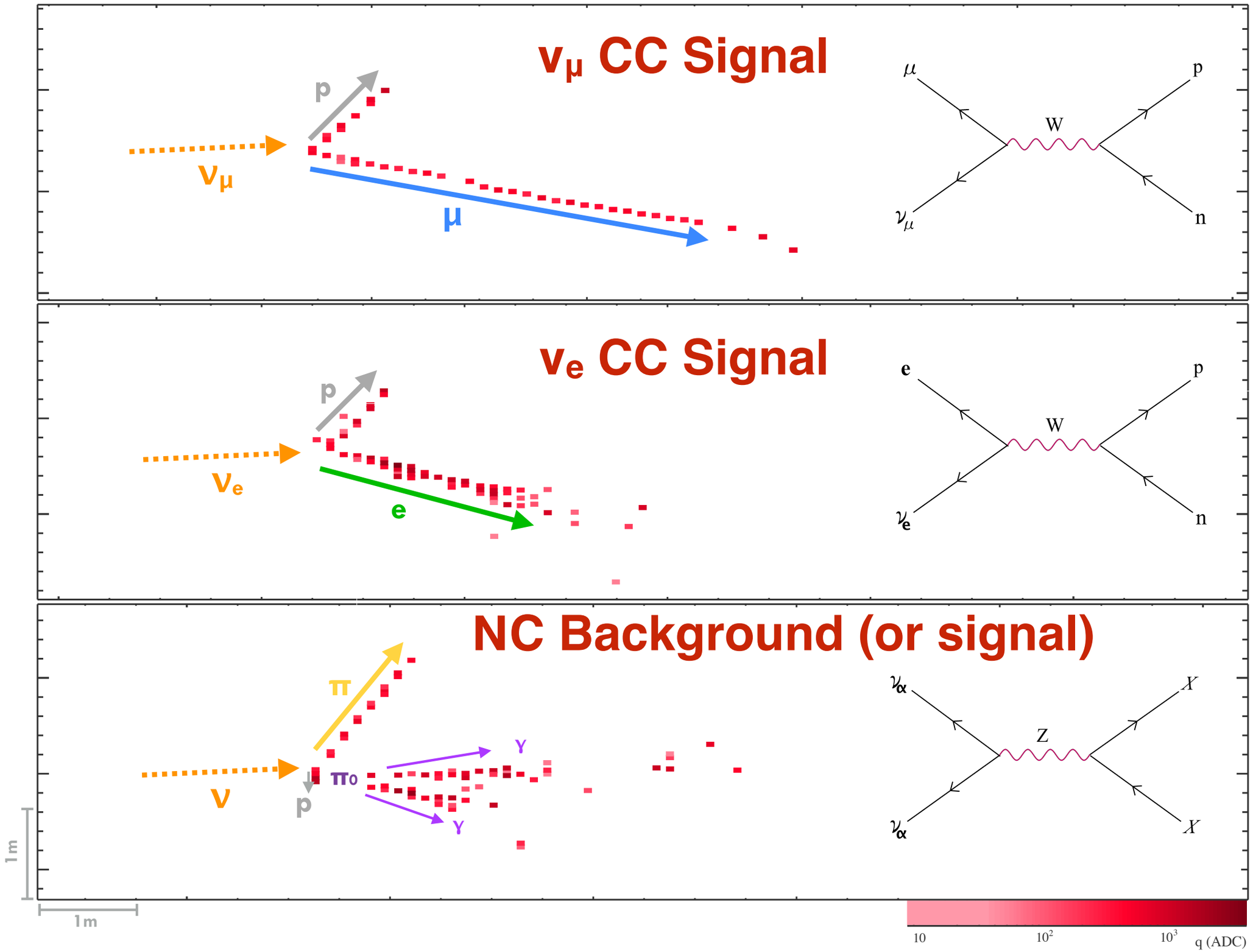






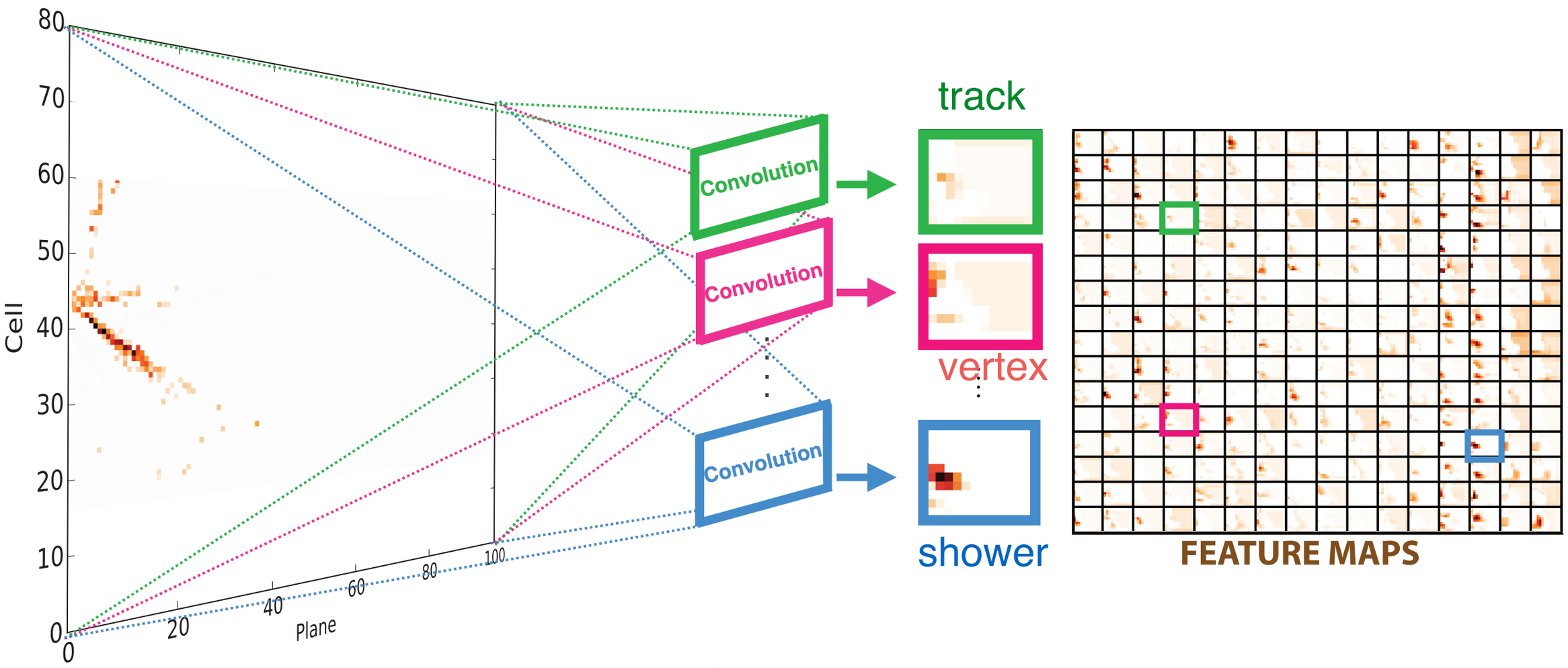
- Two functionally identical detectors
- Extruded plastic cells alternating vertical and horizontal orientation filled with liquid scintillator
- low-z, tracking calorimeter with 65% active mass

Event Topologies



Classifying Neutrino Interactions

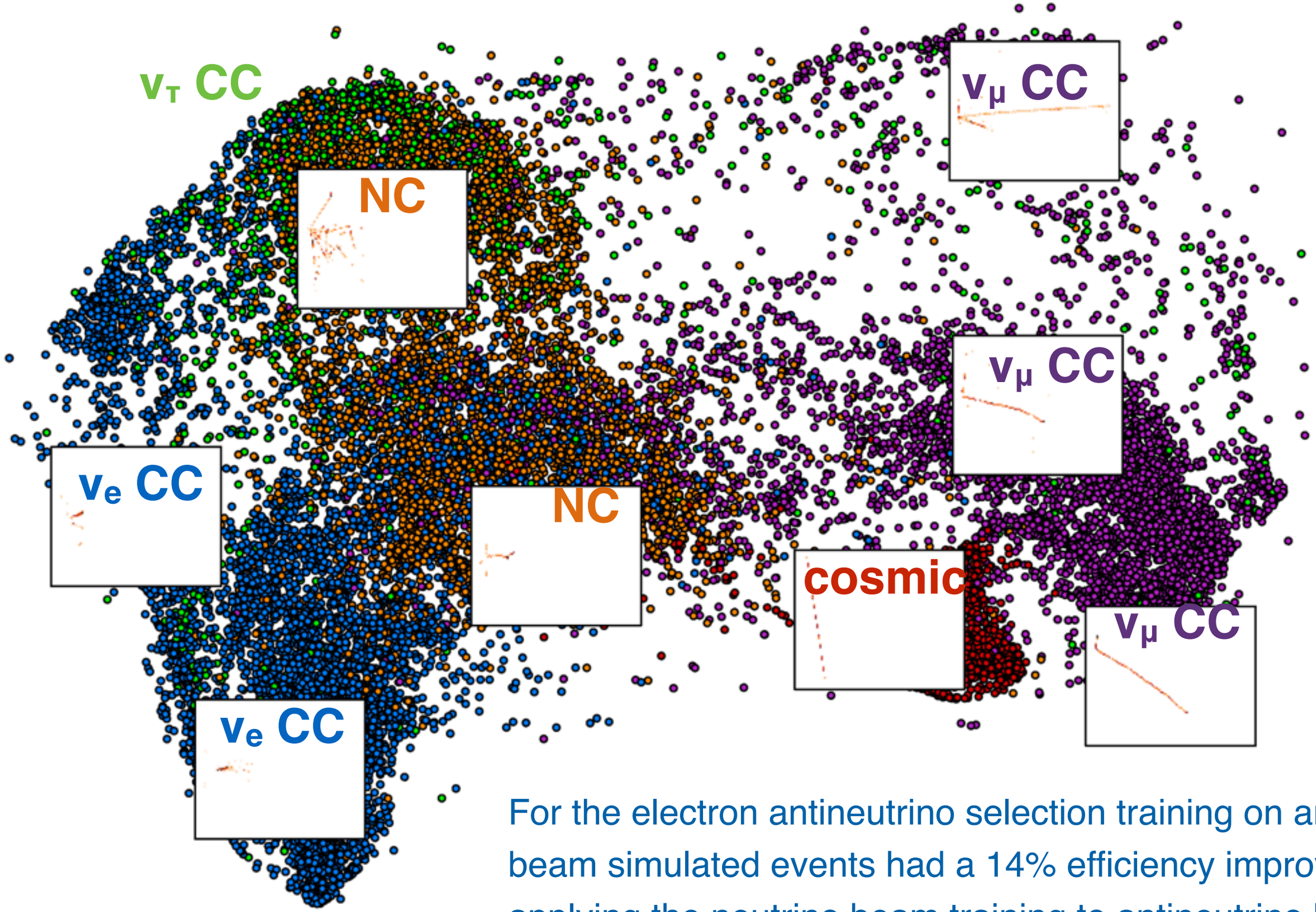
- Classification done with a convolutional neural network based on GoogleNet (known as CVN in NOvA)
- Input: 2D pixel maps of NOvA events
- Output: multi-label classifier based on final state particle multiplicities
- Same network for ν_μ, ν_e, and neutral current selection



A. Aurisano and A. Radovic and D. Rocco et. al, JINST **11** P09001 (2016)

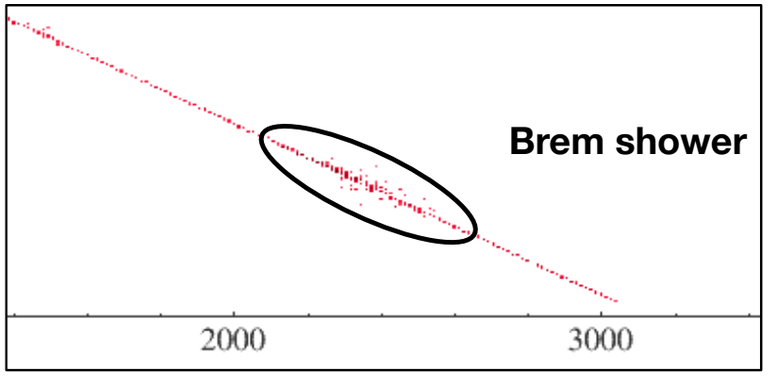
Classifying Neutrino Interactions

Separately trained networks for neutrino and antineutrino beams.

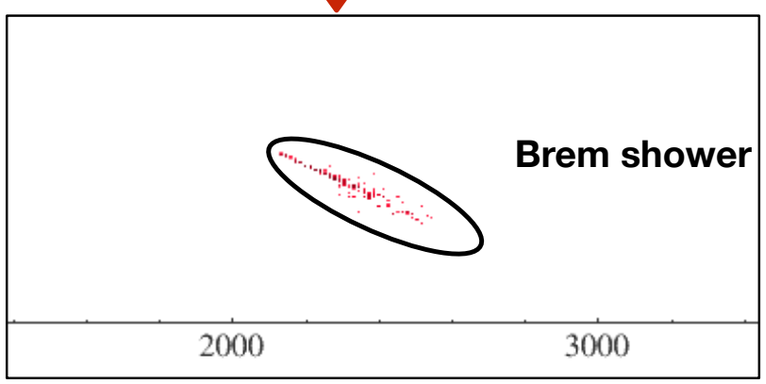


For the electron antineutrino selection training on antineutrino beam simulated events had a 14% efficiency improvement over applying the neutrino beam training to antineutrino beam.

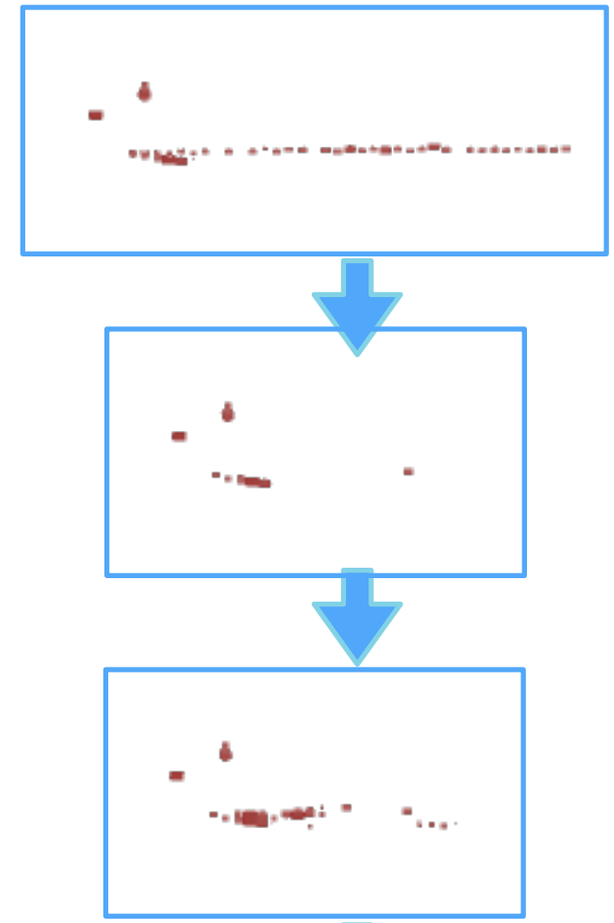
Data Driven Cross-Checks of CVN

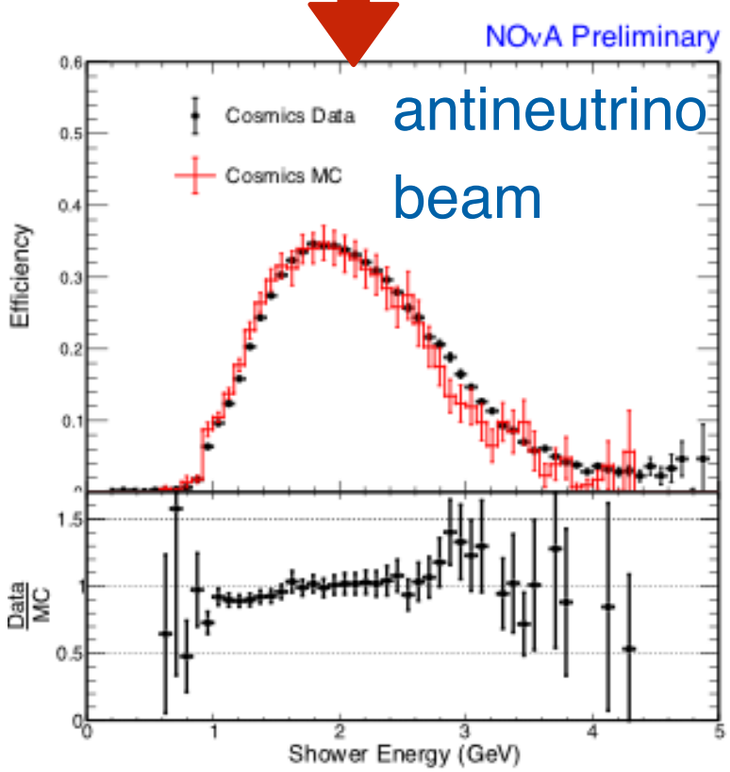


In the **Far Detector** isolate Bremsstrahlung showers in cosmics rays in data and simulation for a known sample of electron showers.

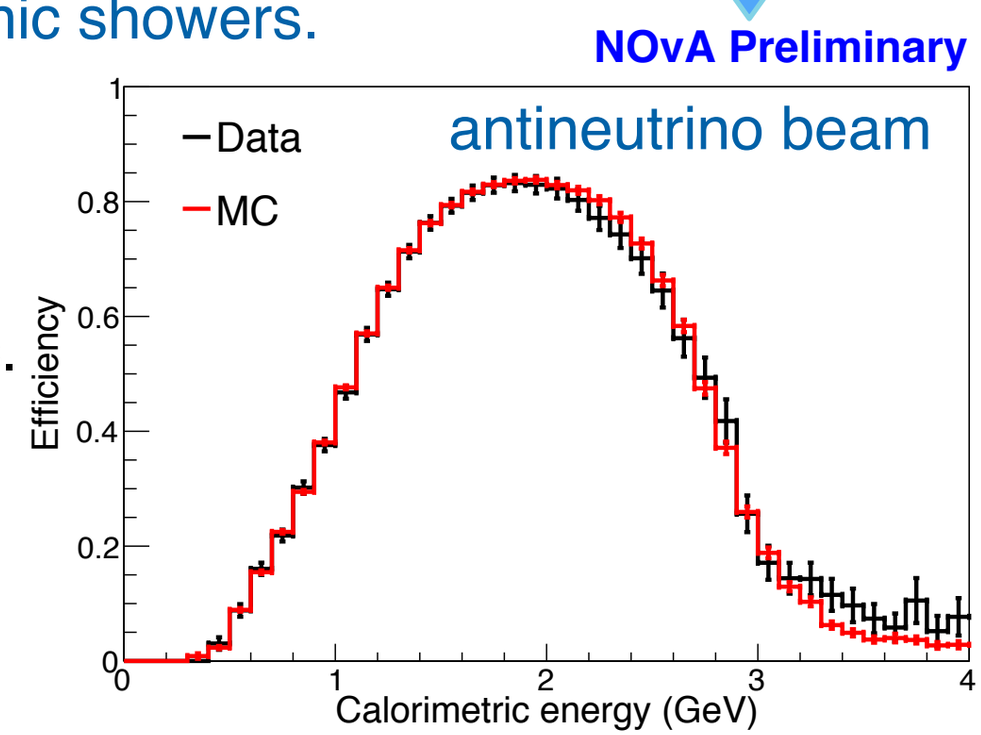


In the **Near Detector** remove muons from selected events and replace with simulated electrons in both data and Monte Carlo. Compares efficiency with real and simulated hadronic showers.





Efficiencies are within systematics in both samples.



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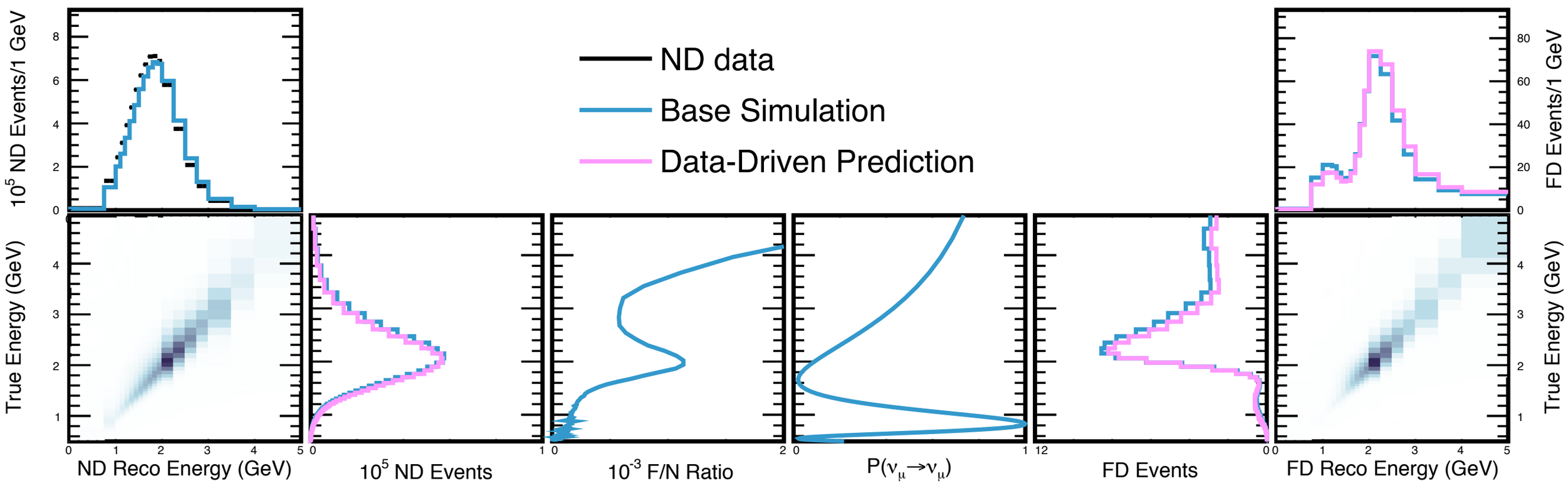
Two Detector Measurement Technique

- Tune cross section model to account for nuclear effects based on a combination of external theory and Near Detector data.
- Use high statistics Near Detector data/MC before oscillations to adjust prediction at FD
- Functionally similar Near and Far Detectors largely cancel the flux and cross section uncertainties.



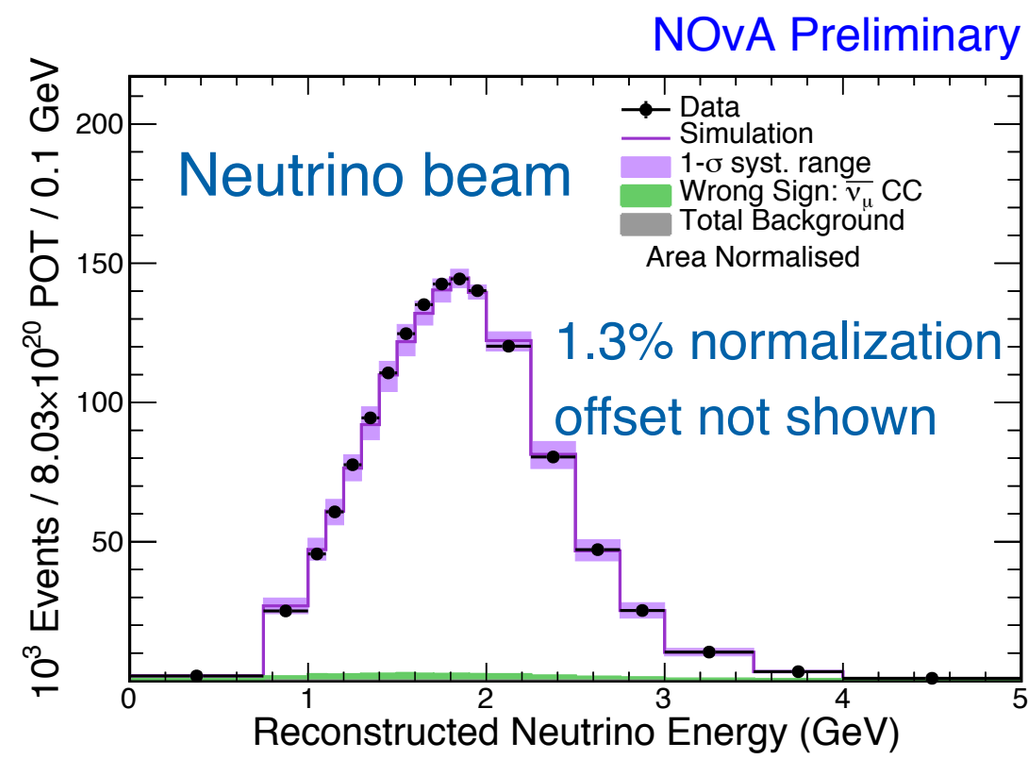
Muon Neutrinos in the Near Detector

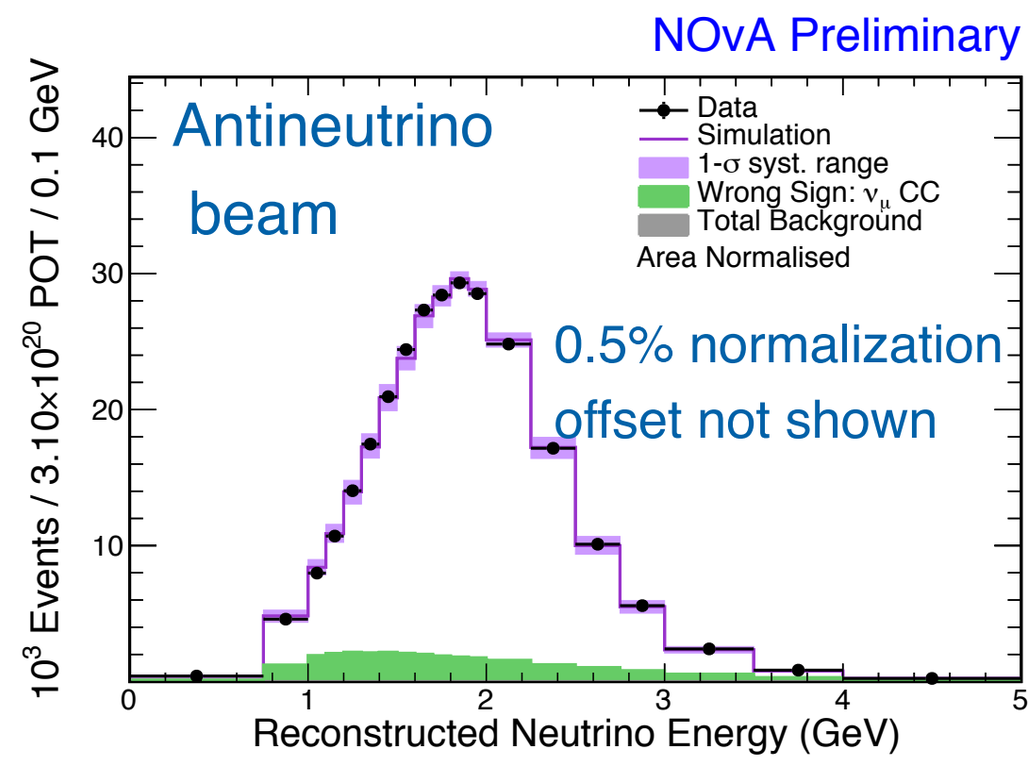
- Reconstructed neutrino energy is estimated from muon length summed with calorimetric energy from hadronic activity.

- Wrong sign contamination in ND is estimated to be 3% for neutrino beam and 11% for antineutrino beam.

- The data is split in four quartiles of hadronic energy fraction as a function of reconstructed neutrino energy.

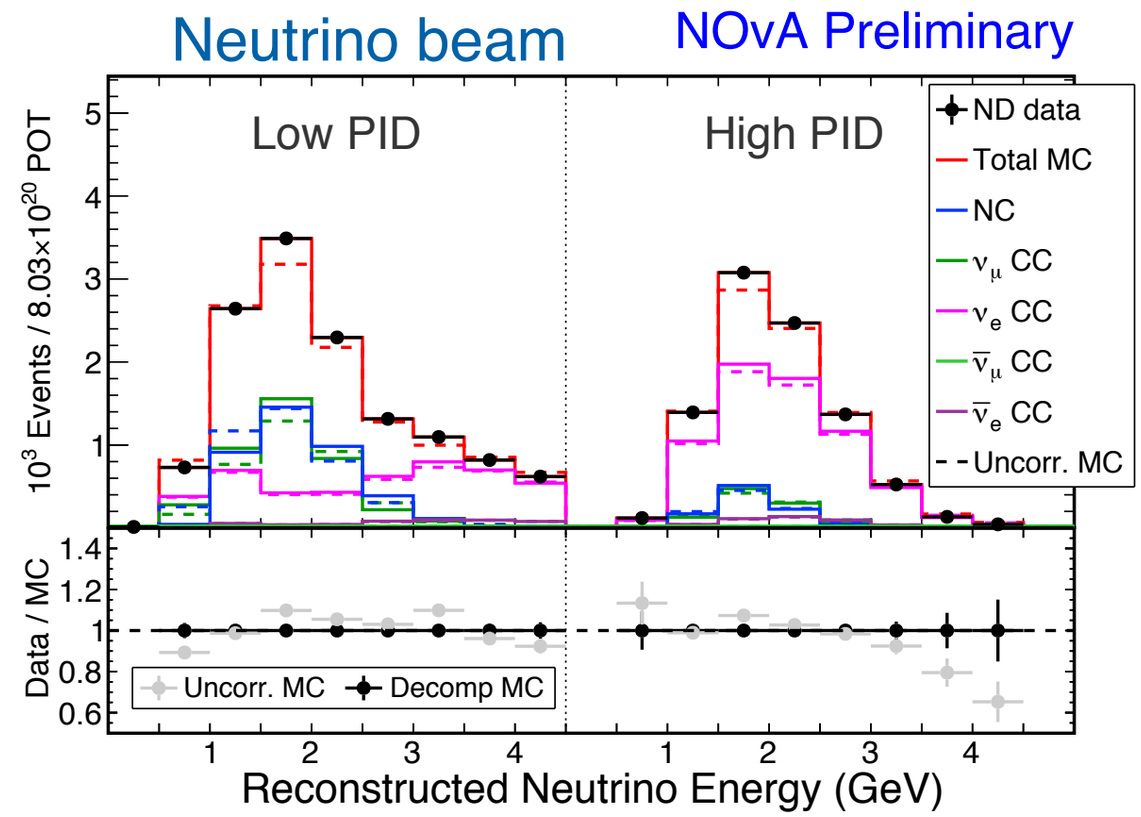
- ND ν_μ data used to predict both the FD ν_μ spectrum and appeared ν_e's.

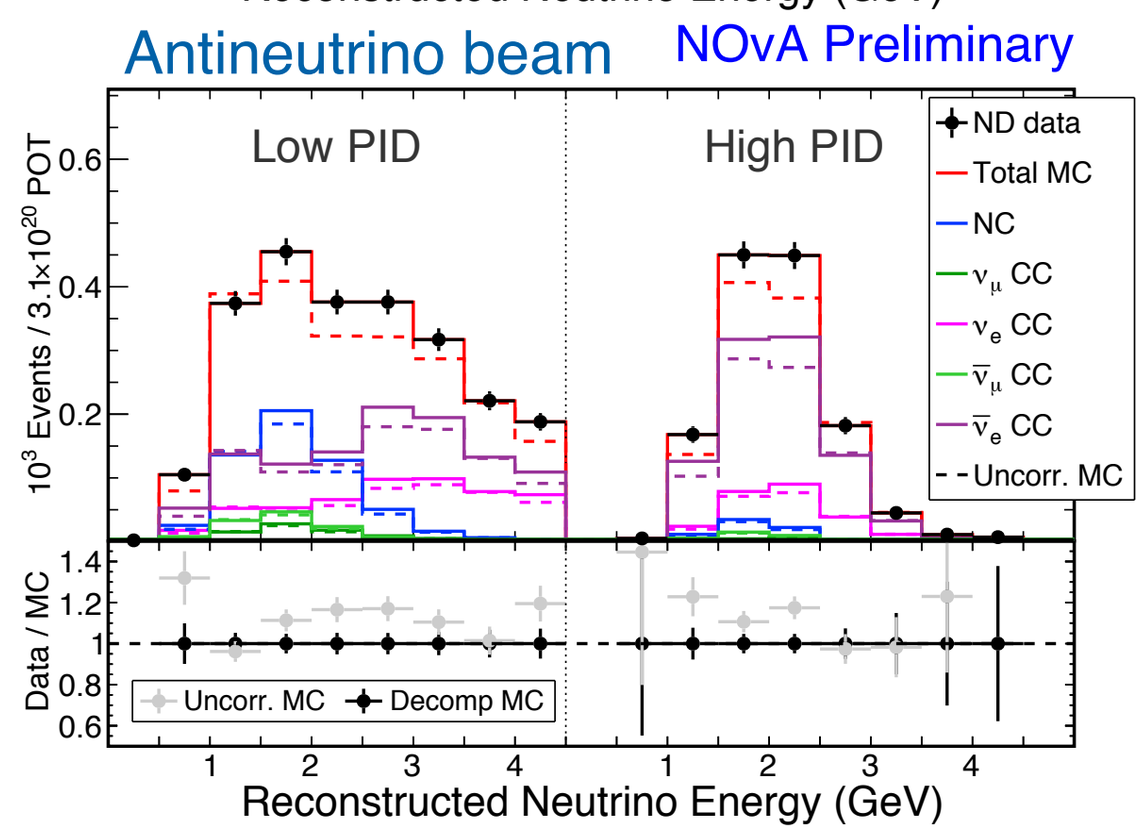




Electron Neutrinos in the Near Detector

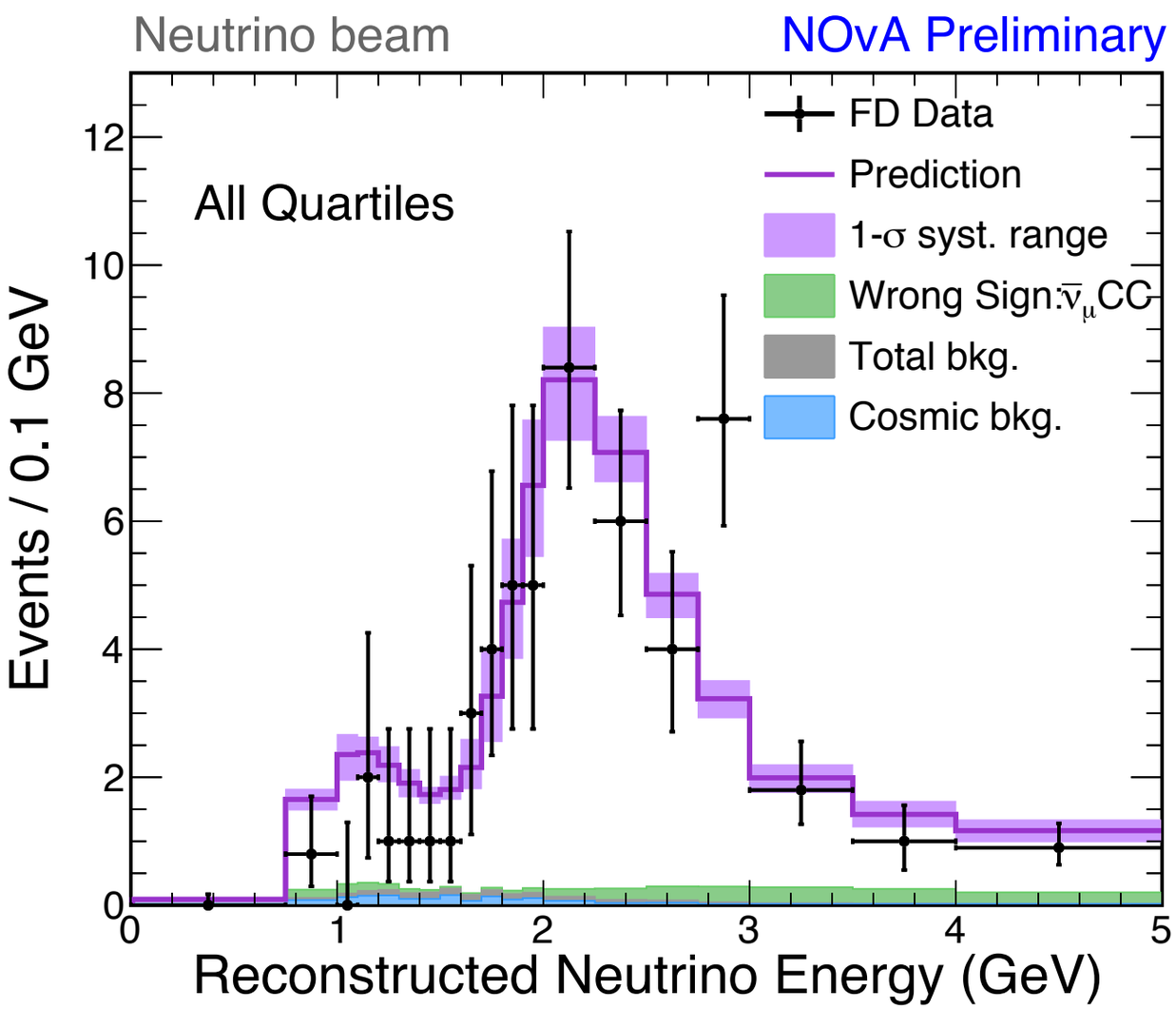
- Split the analysis into regions of high and low particle ID (purity).
- Background components of the FD appeared electron neutrino spectrum
- For the neutrino beam scale the MC:
  - beam electron neutrinos using the muon neutrino spectrum
  - muon neutrinos using the Michel electrons
  - assign remaining data/MC discrepancy to neutral currents
- For the antineutrino beam scale the MC components equally

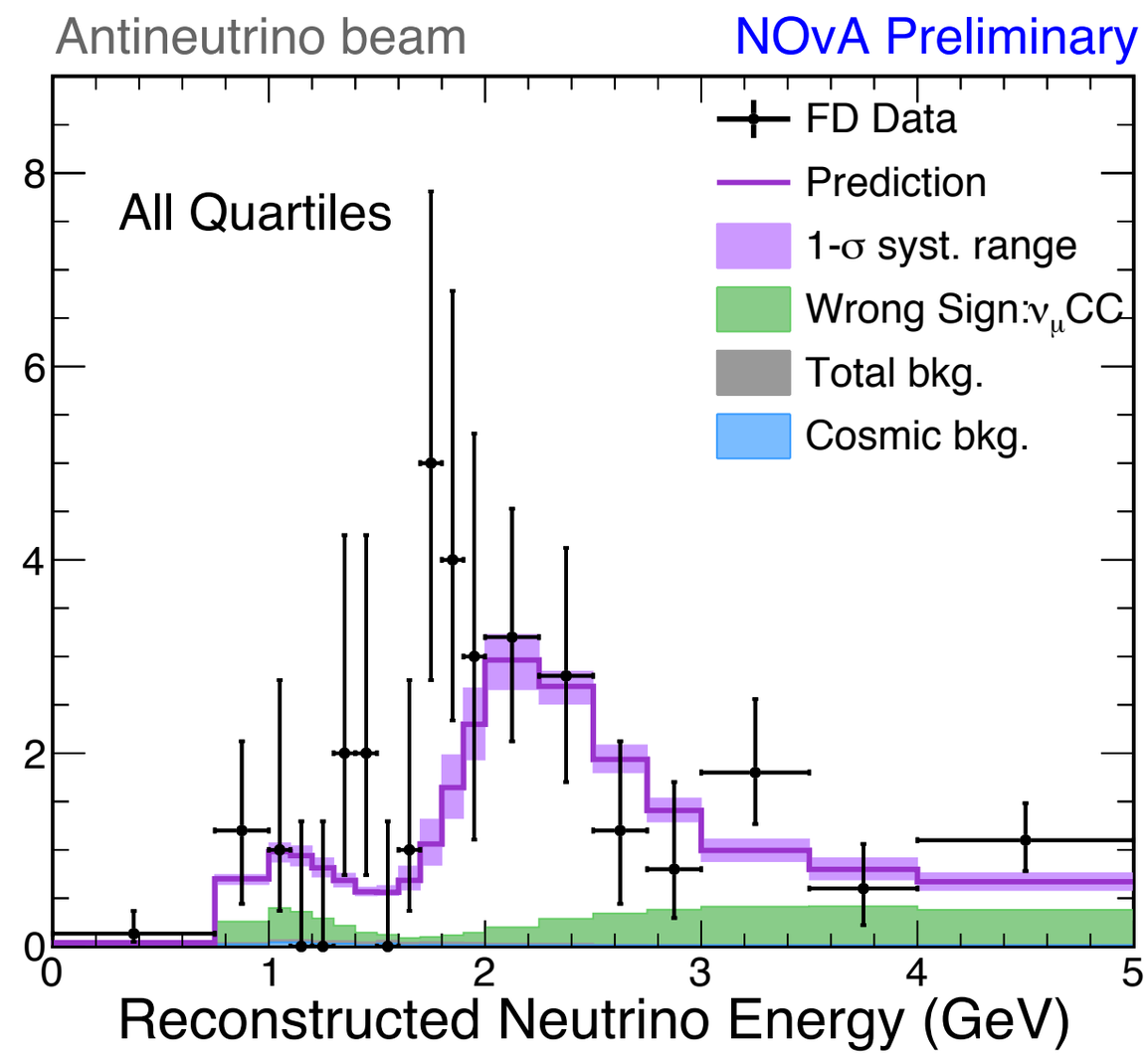




Far Detector ν_μ and $\bar{\nu}_\mu$ Data

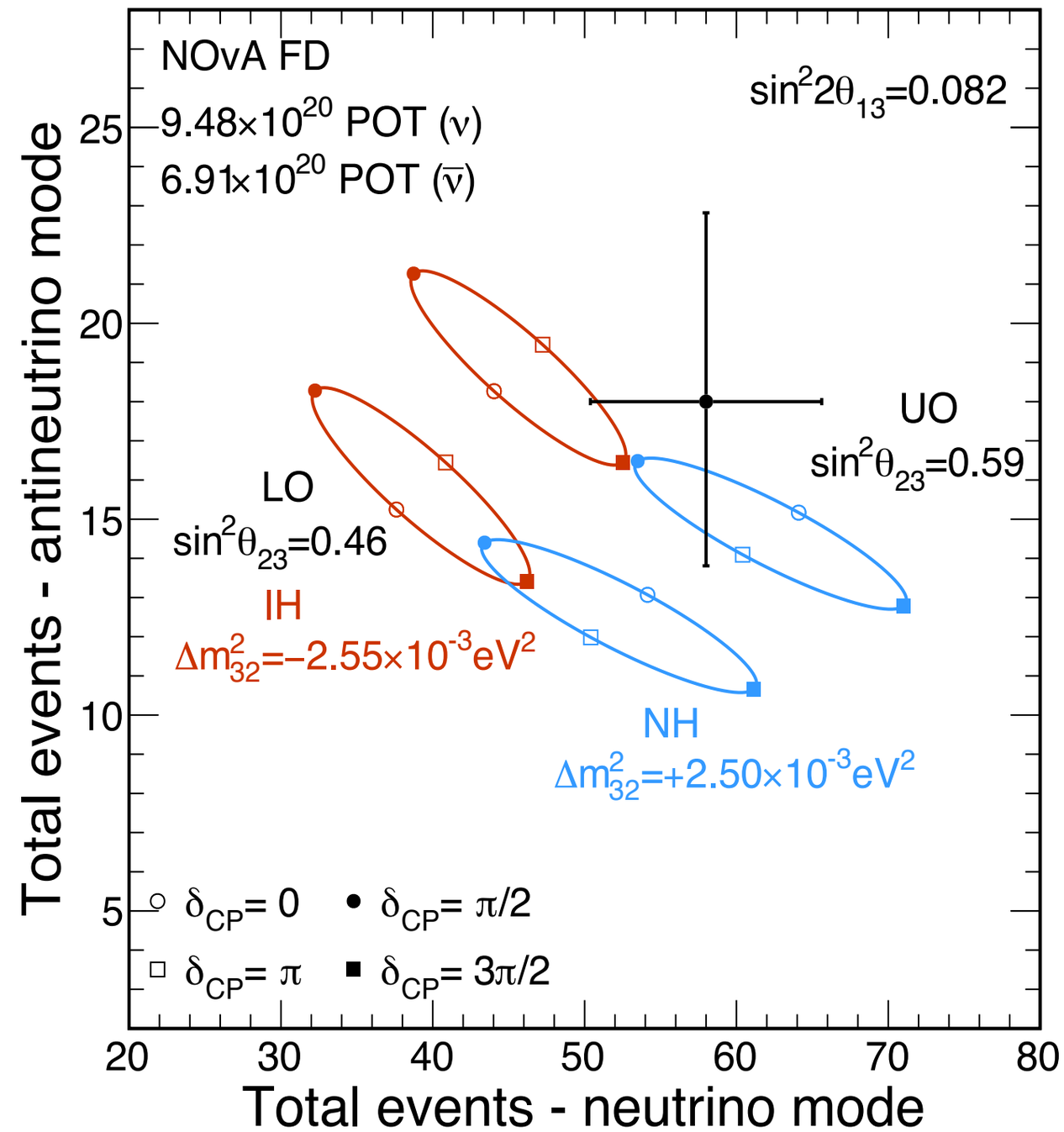
- Each quartile of neutrino and antineutrino beam is extrapolated separately to a Far Detector prediction.
- Cosmic background estimated from timing sideband.
- Observe 113 events in neutrino mode (expect ~730 w/o oscillations),65 events in antineutrino mode (expect ~266 w/o oscillations).





Far Detector ν_e and $\bar{\nu}_e$ Data

- Event counts in the neutrino and antineutrino beams vary according to oscillation parameters
- Measure 58 events in the neutrino beam with a predicted background of 15 events
- Measure 18 events in the antineutrino beam with a predicted background of 5.3 events
- **Greater than 4σ evidence of electron antineutrino appearance in long-baseline beam**



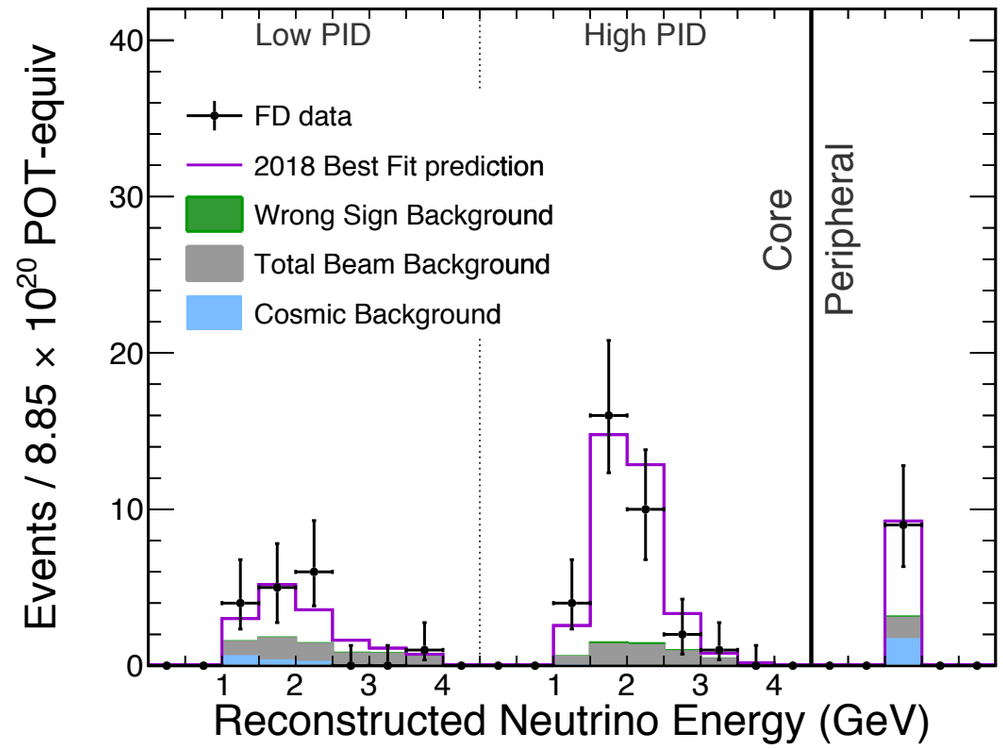
Far Detector ν_e and $\bar{\nu}_e$ Data

Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

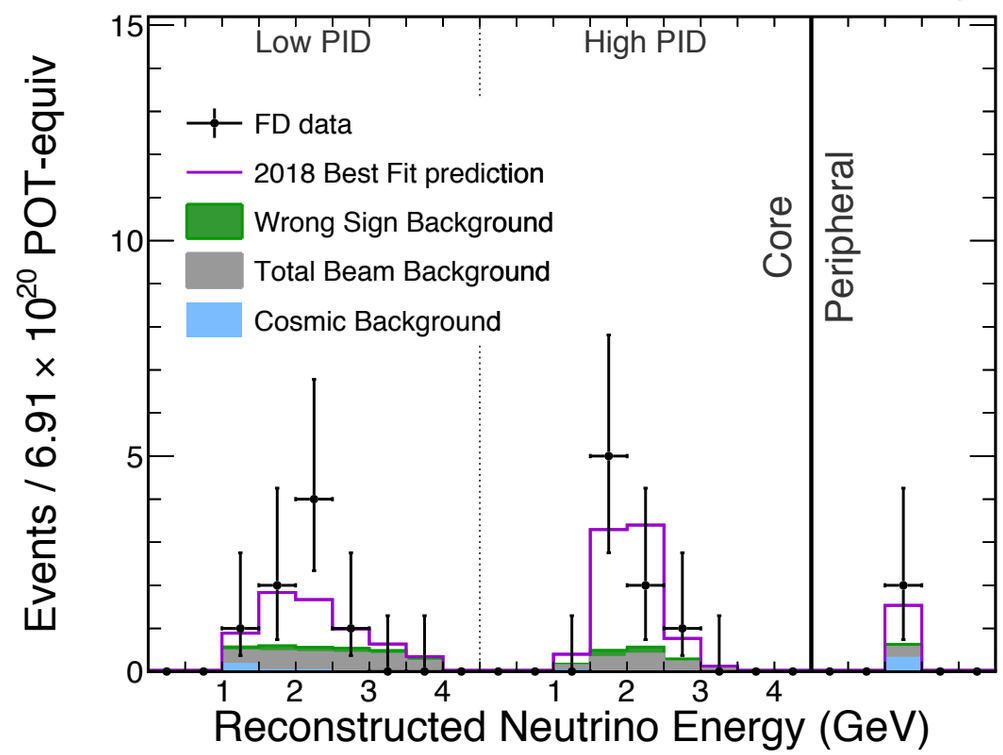
Total Observed	18	Range
Total Prediction	15.9	10-22
Wrong-sign	1.1	0.5-1.5
Beam Bkgd.	3.5	
Cosmic Bkgd.	0.7	
Total Bkgd.	5.3	4.7-5.7

- **Greater than 4σ evidence of electron antineutrino appearance in long-baseline beam**

Neutrino Beam NOvA Preliminary

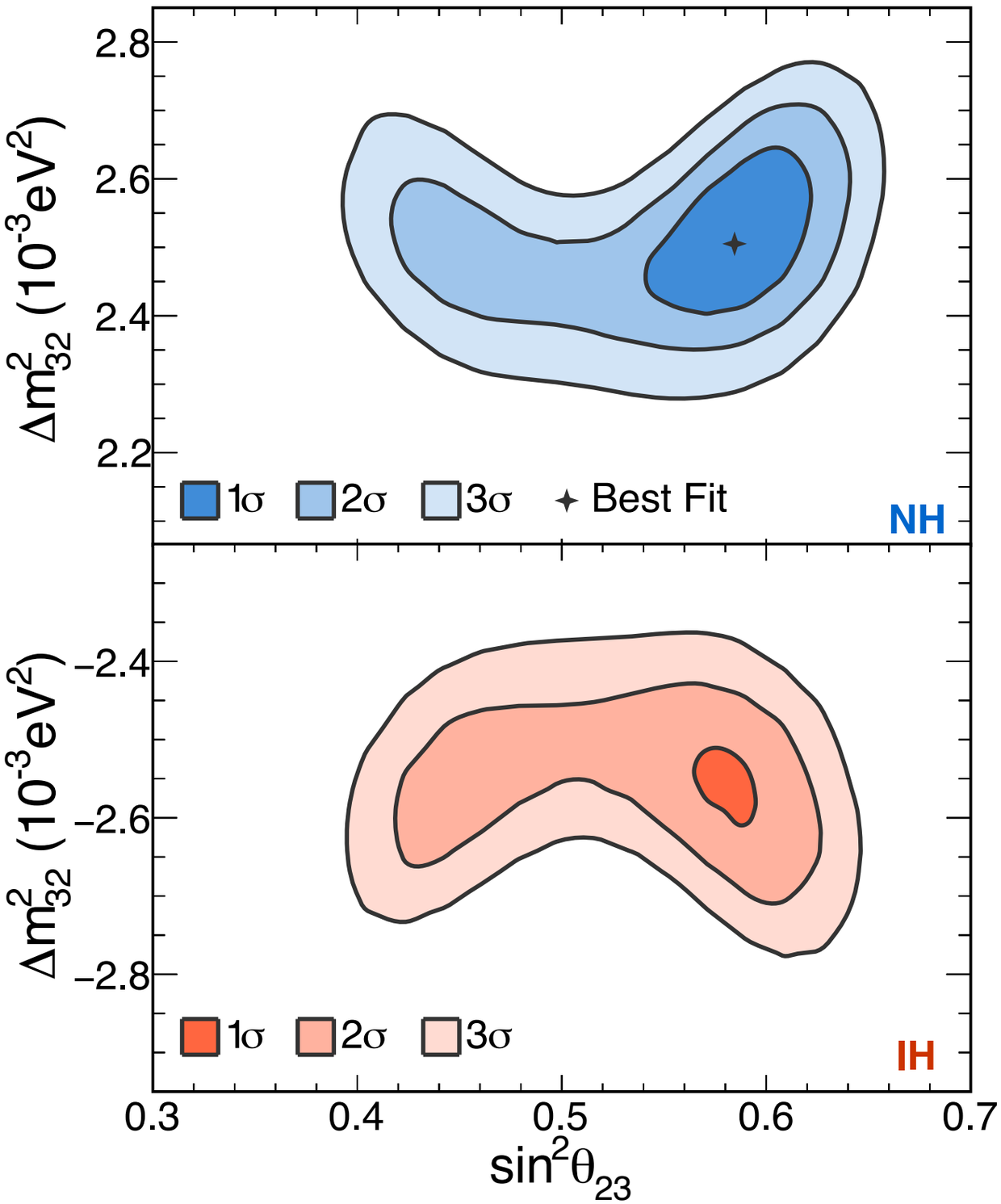


Antineutrino Beam NOvA Preliminary



Allowed Oscillation Parameters from joint $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ fit

NOvA Preliminary



Best fit:

Normal Hierarchy

$\sin^2\theta_{23} = 0.58 \pm 0.03$ (Upper Octant)

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

Prefer non-maximal θ_{23} at 1.8σ.

Disfavor lower octant at similar level.

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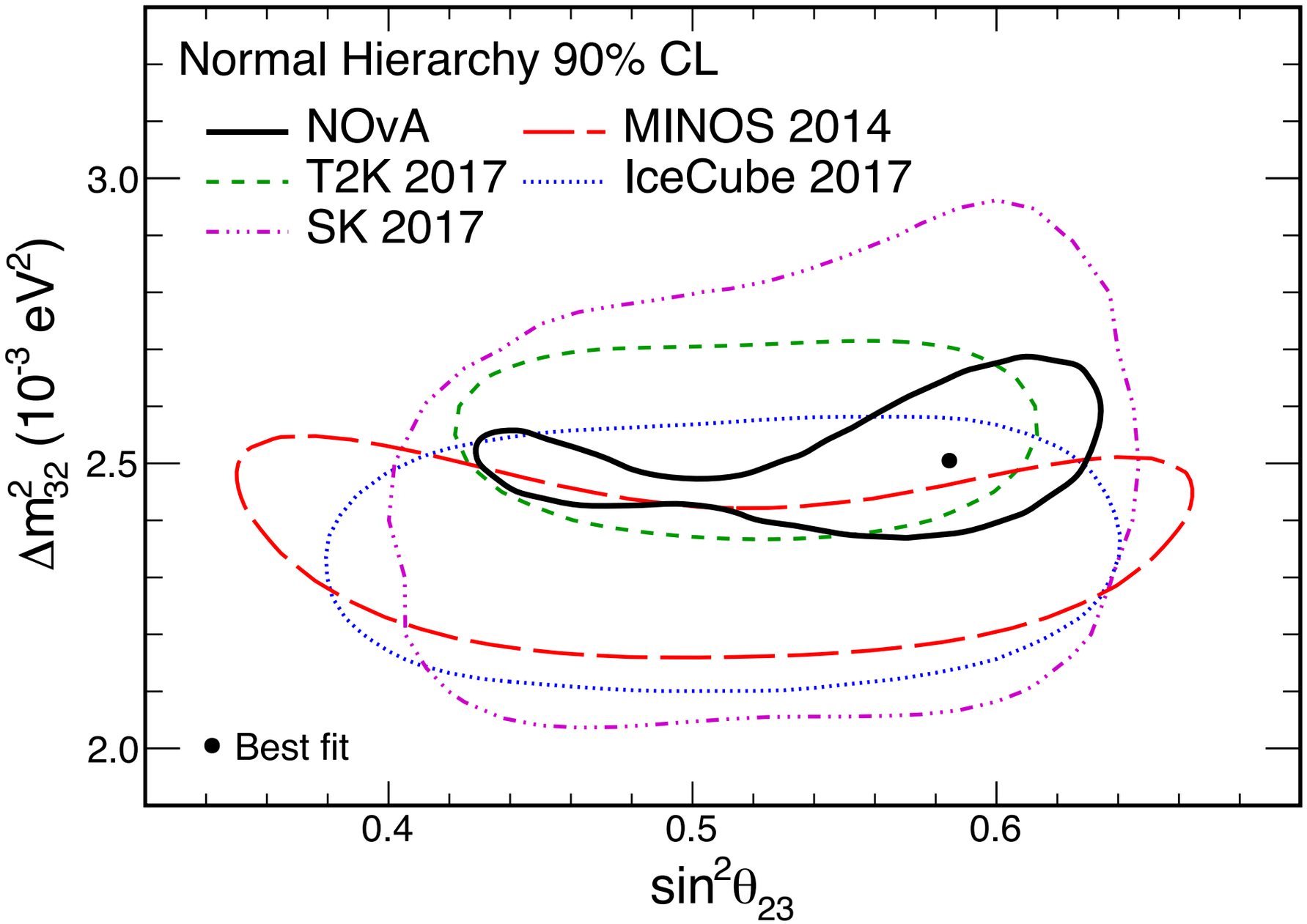
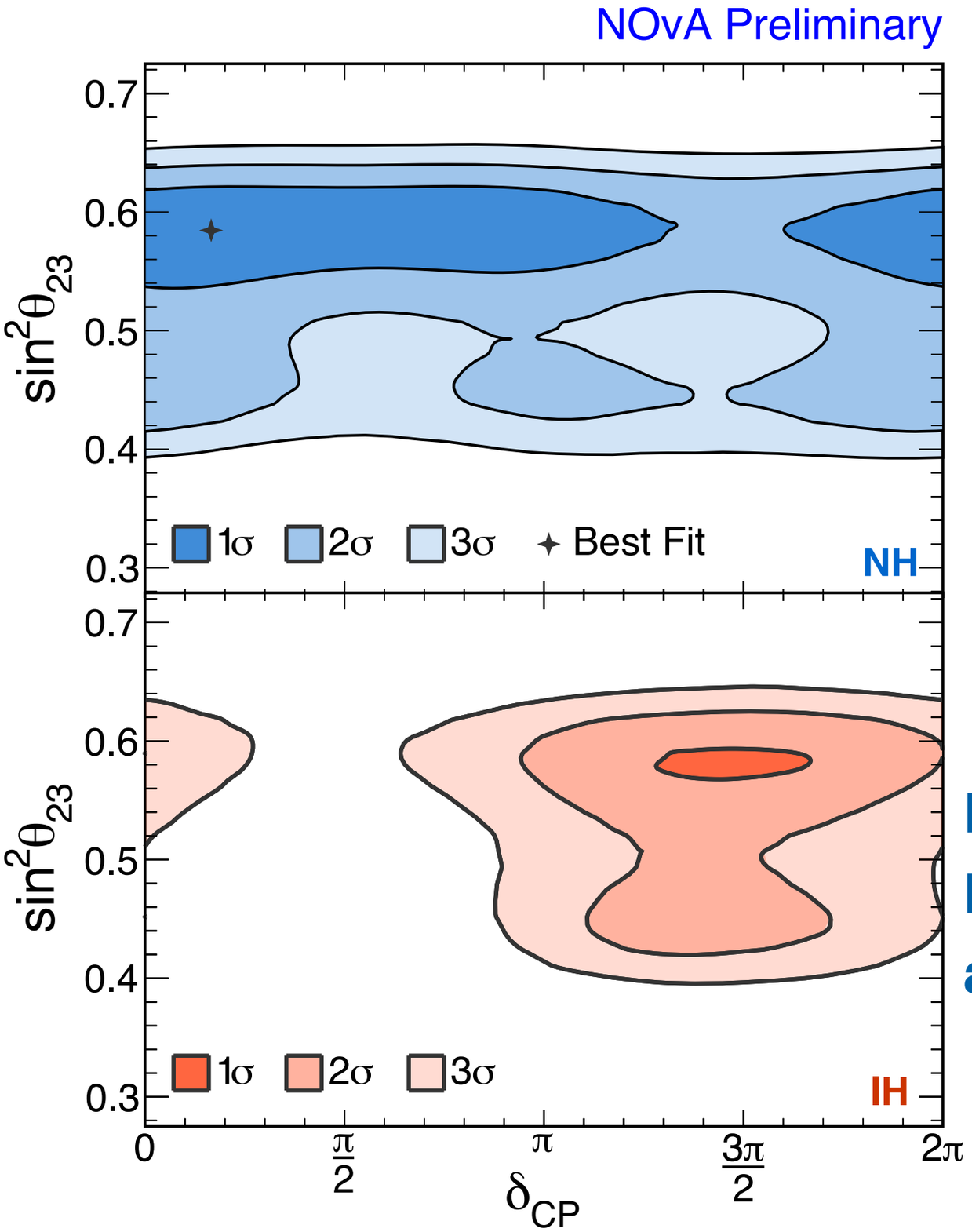
Allowed Oscillation Parameters from joint $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ fit

NOvA Preliminary



Consistent with other long-baseline and atmospheric experiments in 90% allowed regions.

Allowed Oscillation Parameters from joint $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ fit



- **Best fit:**
  Normal Hierarchy
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (Upper Octant)
  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ eV^2$
  $\delta_{CP} = 0.17\pi$

Prefer normal hierarchy by 1.8σ

Disfavor δ=π/2 in the inverted hierarchy at > 3σ

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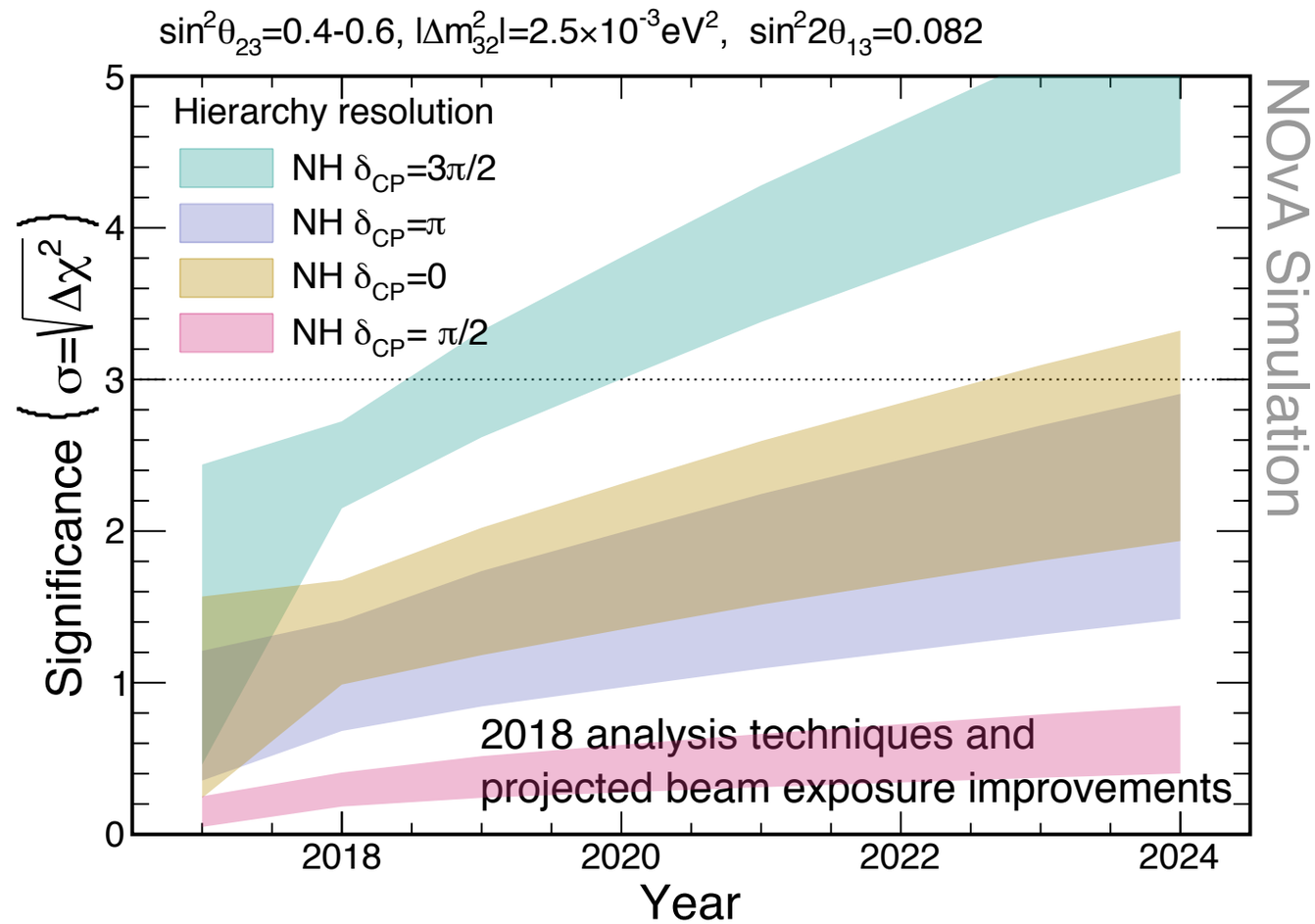
Looking Forward

- Now running antineutrino beam. Plan to run 50% neutrino and 50% antineutrino after 2018.
- Extending NOvA running to 2024 and planned accelerator improvements enhances reach.
- Sensitivity depends strongly on true parameter values.
- 3σ sensitivity possible to the hierarchy by 2020 with favorable parameters. 30-50% of CP parameter covered by 2024.



NOvA Test Beam Program

- The test beam program feeds into NOvA analysis improvements though reduction of systematics, validation and training of reconstruction and machine learning algorithms, and simulation improvements.
- Construction and commissioning underway
- Beam planned for first half of 2019, 2 million particles.

Conclusions

- First NOvA antineutrino data (6.9×10^{20} POT) has been analyzed together with 8.85×10^{20} POT of neutrino data.
- We observe >4σ evidence of electron antineutrino appearance in long-baseline beam in NOvA's first antineutrino result.
- A joint appearance and disappearance analysis for the combined dataset:
  - Prefers Normal Hierarchy at 1.8σ and disfavor Inverted Hierarchy at $\delta_{CP} = \pi/2$ at > 3σ.
  - Disfavor maximal mixing of θ_{23} at 1.8σ and the lower octant at a similar level.
- NOvA can reach 3σ sensitivity for the mass hierarchy by 2020 for the most favorable parameters and cover more then 30% of the CP phase space by 2024.
- NOvA test beam campaign under construction for winter 2018 to inform systematics and analysis techniques.

More Details on NOvA

Talks at New Perspectives

- J. Vasel “NOvA in 10 Minutes”
- M. Groh “NOvA Reconstruction using Deep Learning”
- D. Torbunov “NOvA Muon Disappearance Results 2018”
- B. Howard “New electron (anti-)neutrino appearance analysis from NOvA
- D. Doyle “Acclerating Feldman-Cousins on NOvA using NERSC Supercomputers
- J. Hewes “Search for sterile neutrinos in NOvA neutrino data”
- R. Keloth “NOvA’s Short-Baseline Tau-Neutrino Appearance Search”

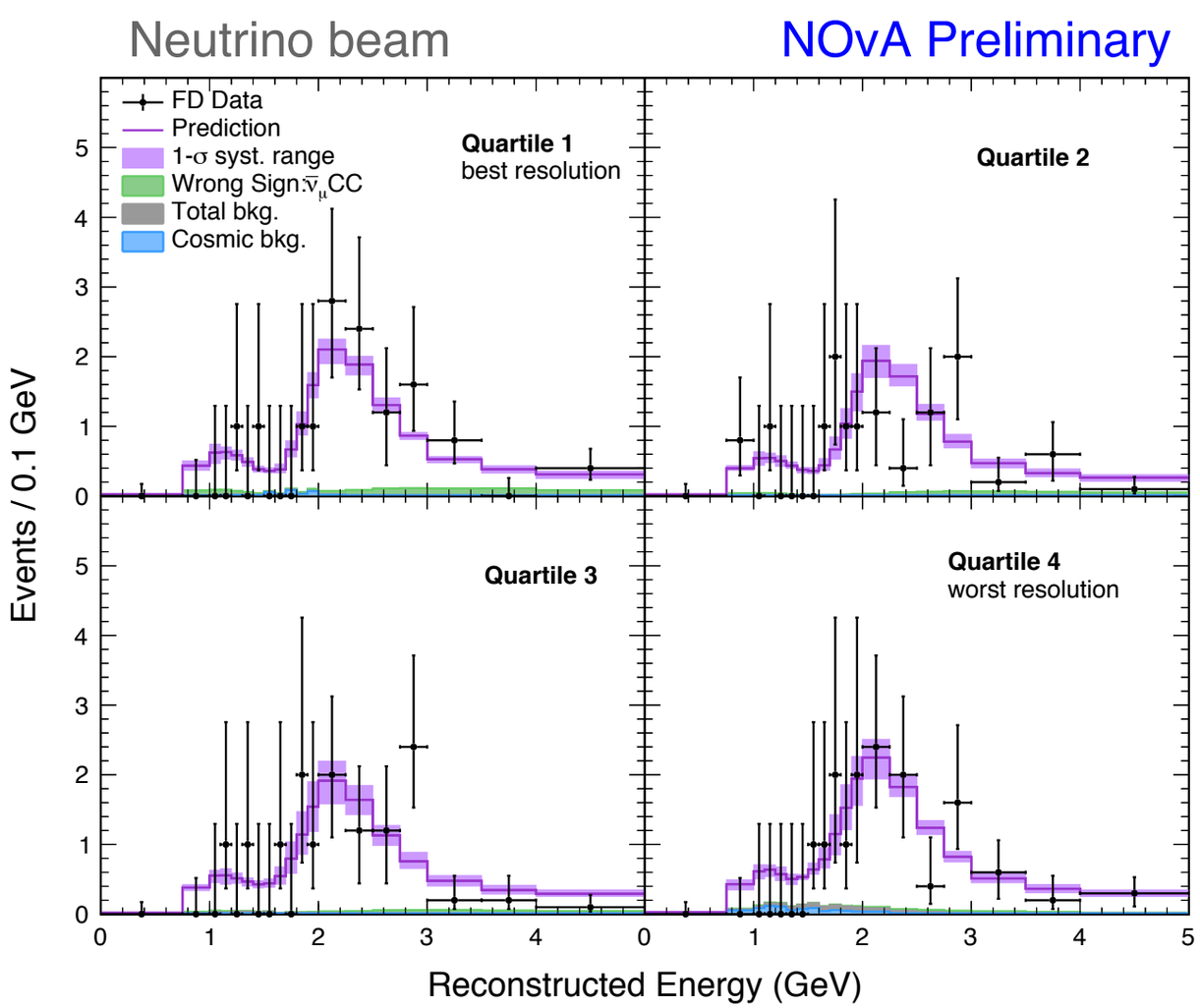
Posters at Users Meeting

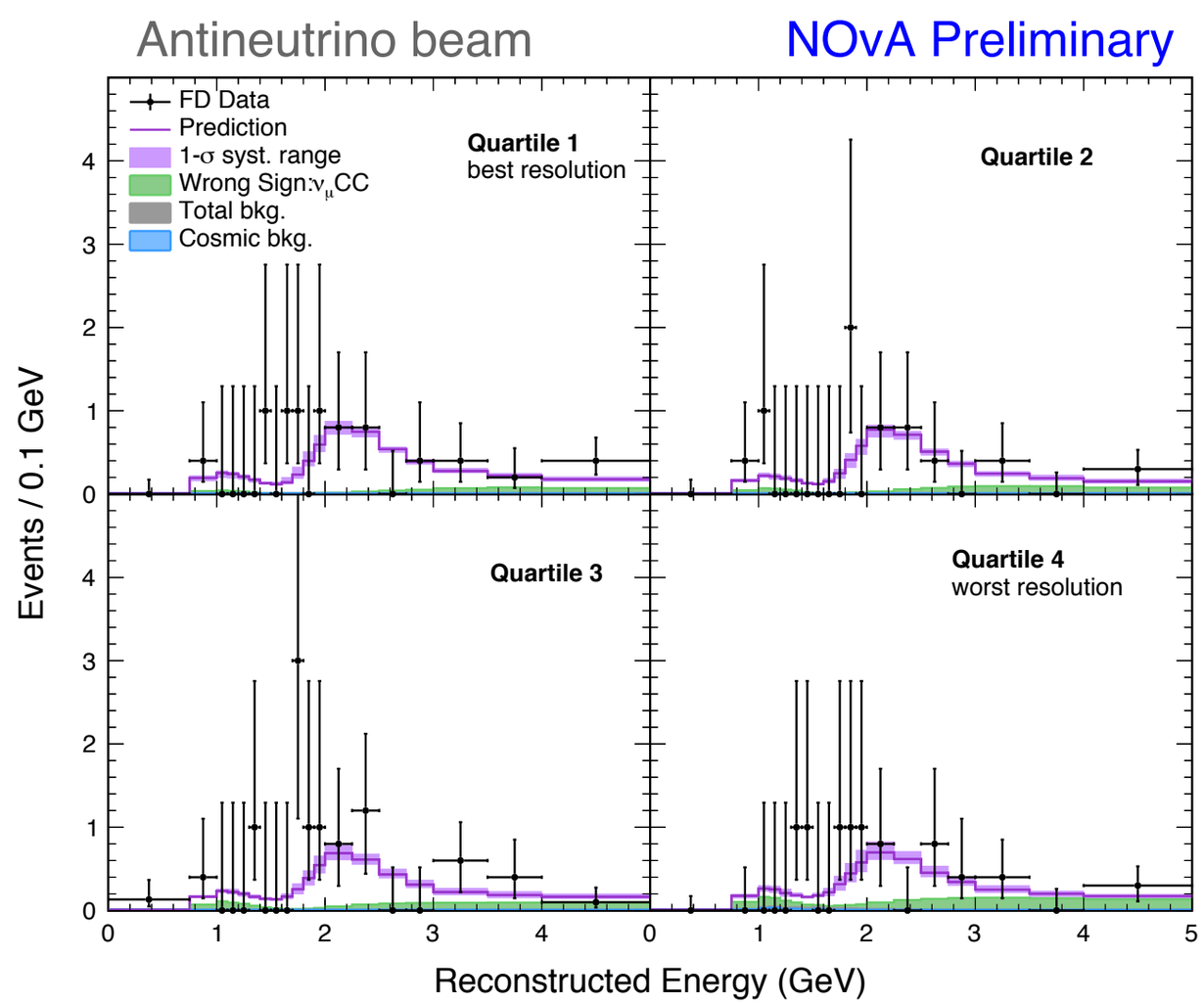
- R. Gandrajula “First measurement of oscillation parameters with neutrino and antineutrino beam in NOvA”
- D. Torbunov “NOvA Muon Disappearance Results 2018”
- S. Edayath “Long Baseline Sterile Neutrino Search in the NOvA Experiment”
- S. Lin “Status of the Incluse Electron and Muon Neutrino Charged-Current Cross-Section Measurements in the NOvA Near Detector”

Thank You

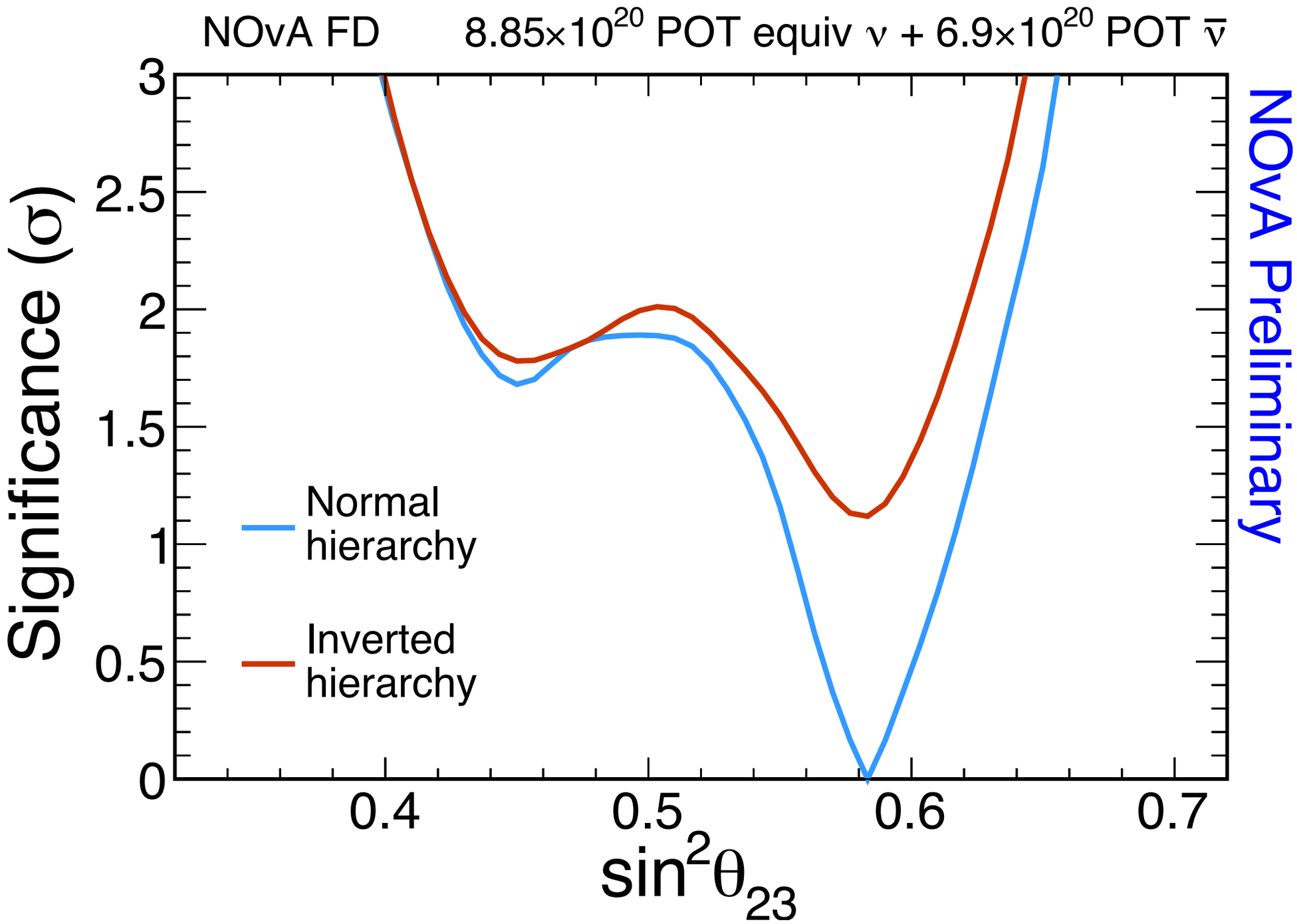
Far Detector ν_μ and $\bar{\nu}_\mu$ Data

- Each quartile of neutrino and antineutrino beam is extrapolated separately to a Far Detector prediction.
- Cosmic background estimated from timing sideband.
- Observe 113 events in neutrino mode (expect 730 +38/-49(syst.) w/o oscillations),65 events in antineutrino mode (expect 266 +12/-14(syst.) w/o oscillations).





Allowed Oscillation Parameters from joint $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ fit



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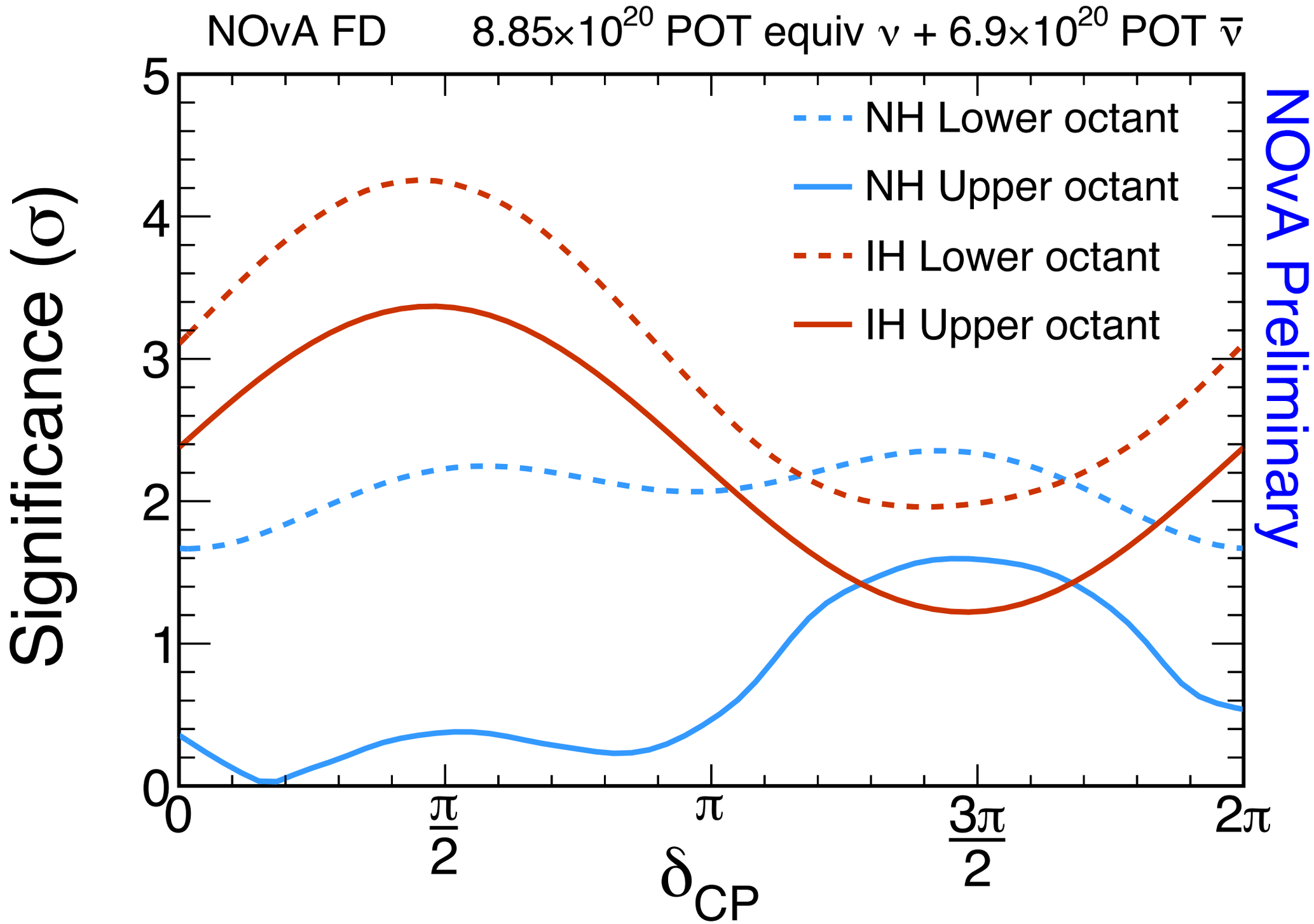
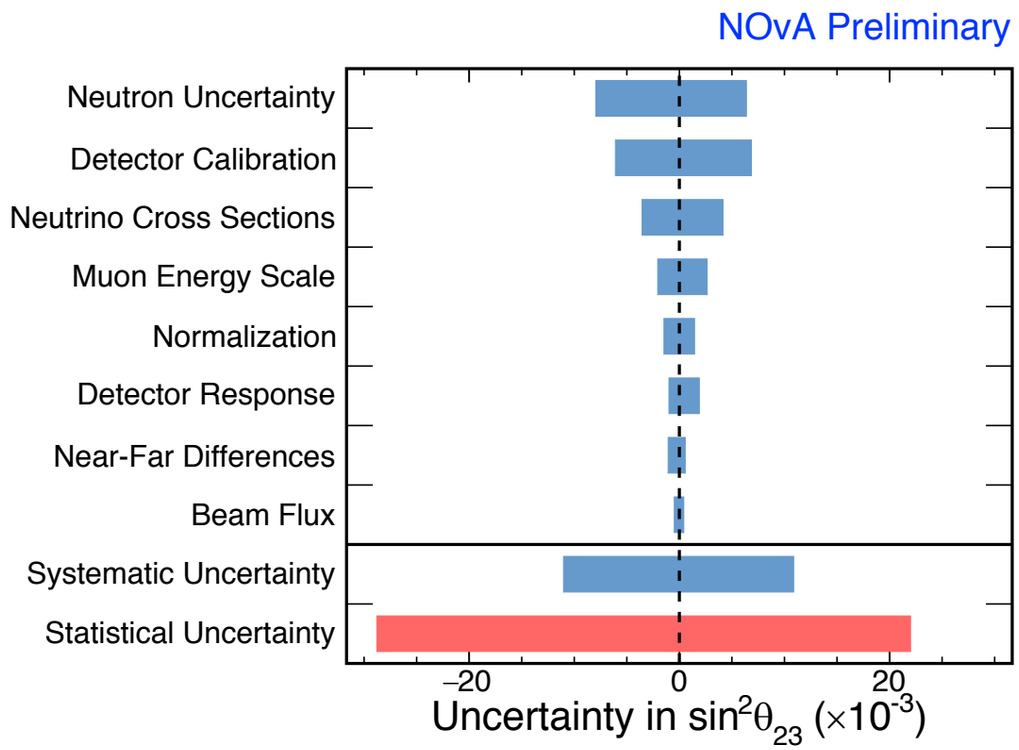
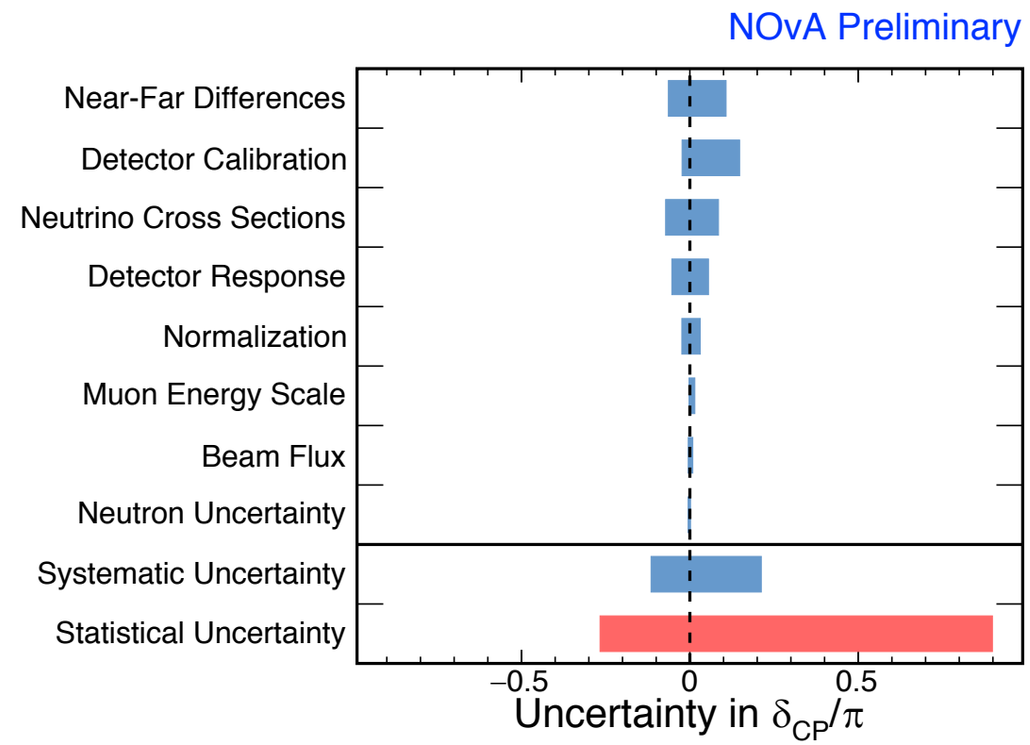
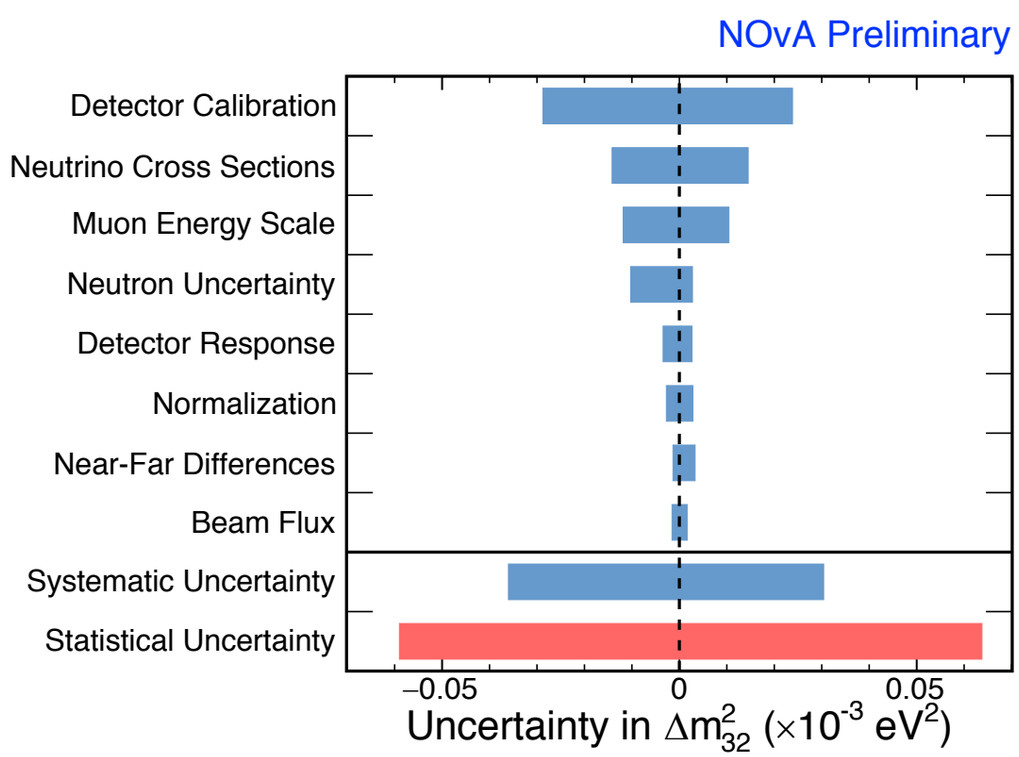


Systematic Uncertainties

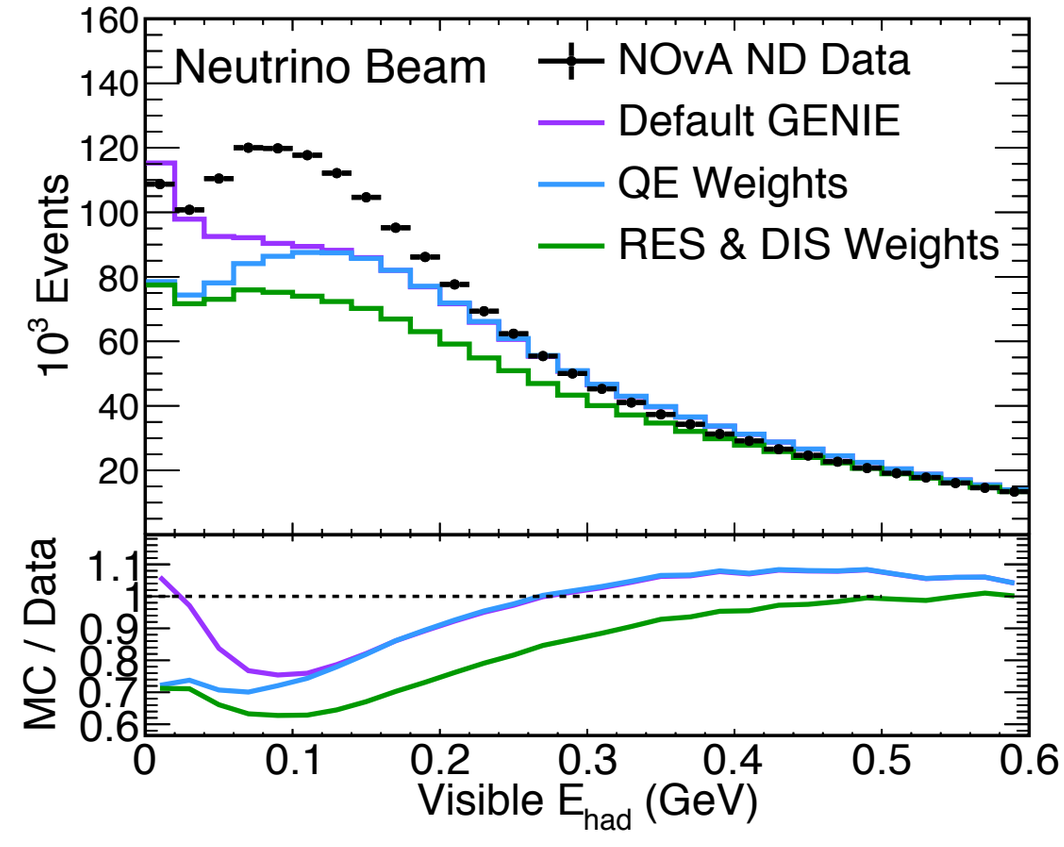


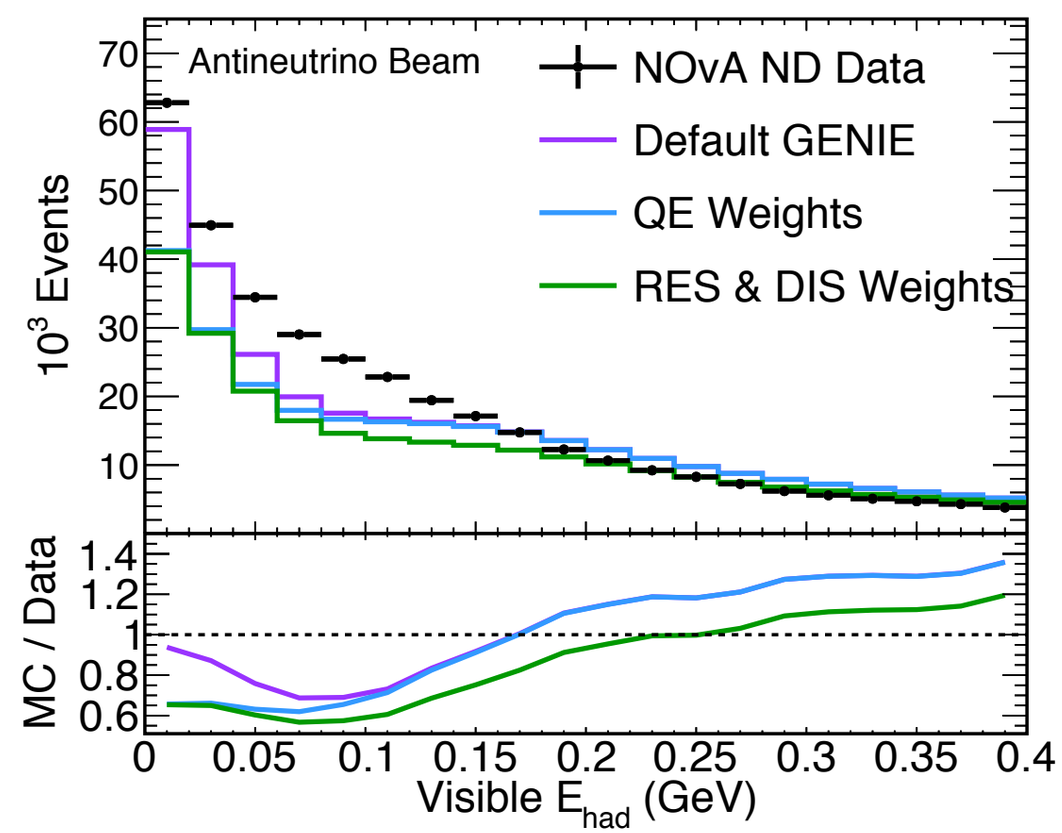




Neutrino Interaction Tuning

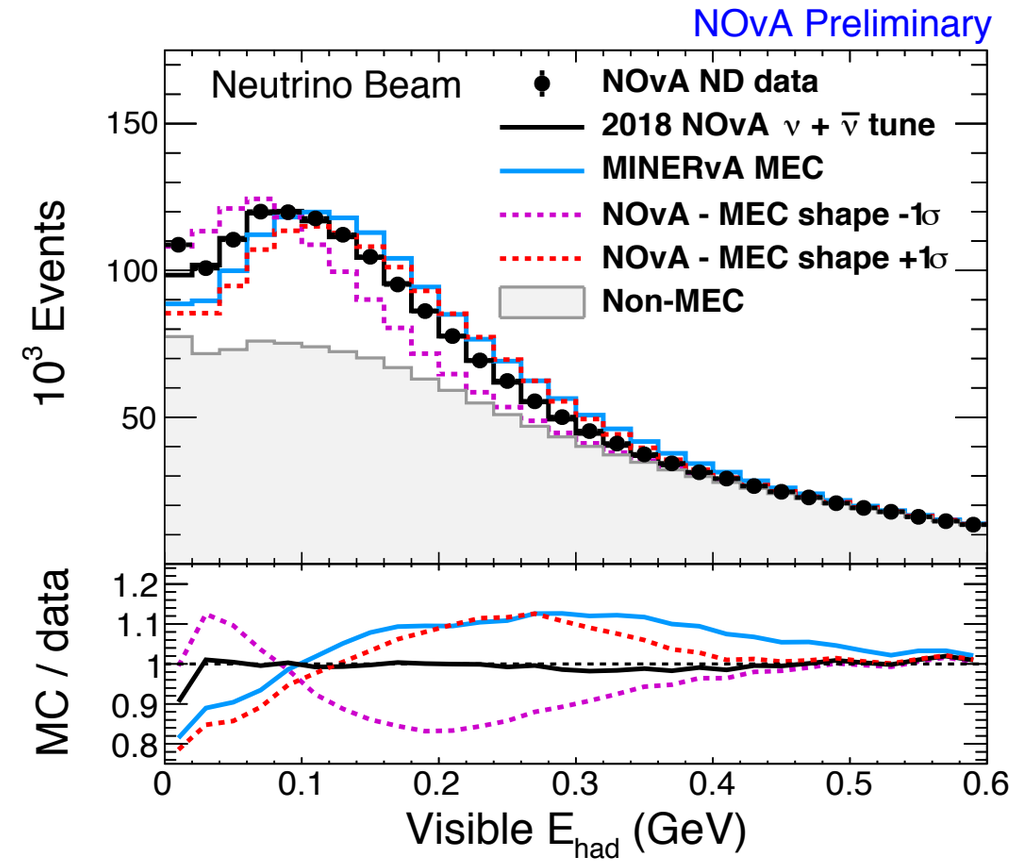
- The tuning is done independently for the neutrino vs antineutrino beam samples.
- Various corrections and tunings are applied:
  - Correct quasielastic (QE) component to account for effect of long-range nuclear correlations using model of València group via work of R. Gran (MINERvA) [https://arxiv.org/abs/1705.02932]
  - Apply same long-range effect as for QE to resonant (RES) baryon production.
  - Nonresonant inelastic scattering (DIS) at high invariant mass (W>1.7 GeV/c^2) weighted up 10% based on NOvA data.

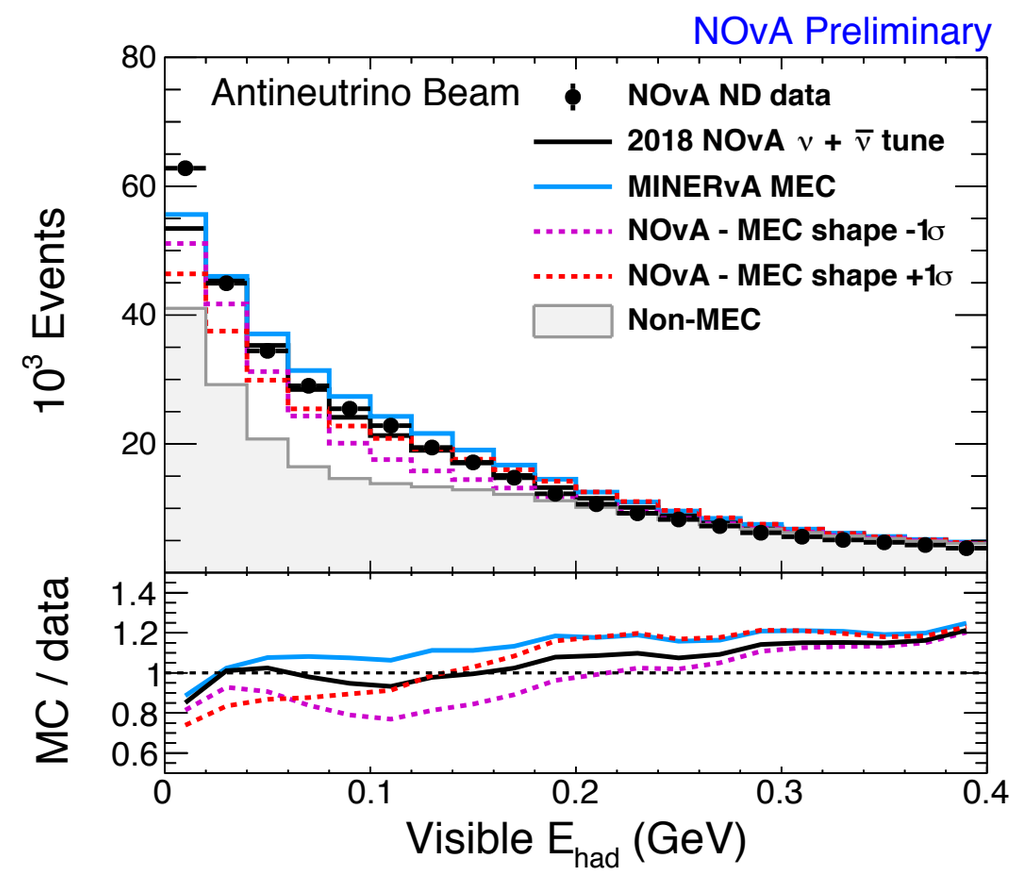




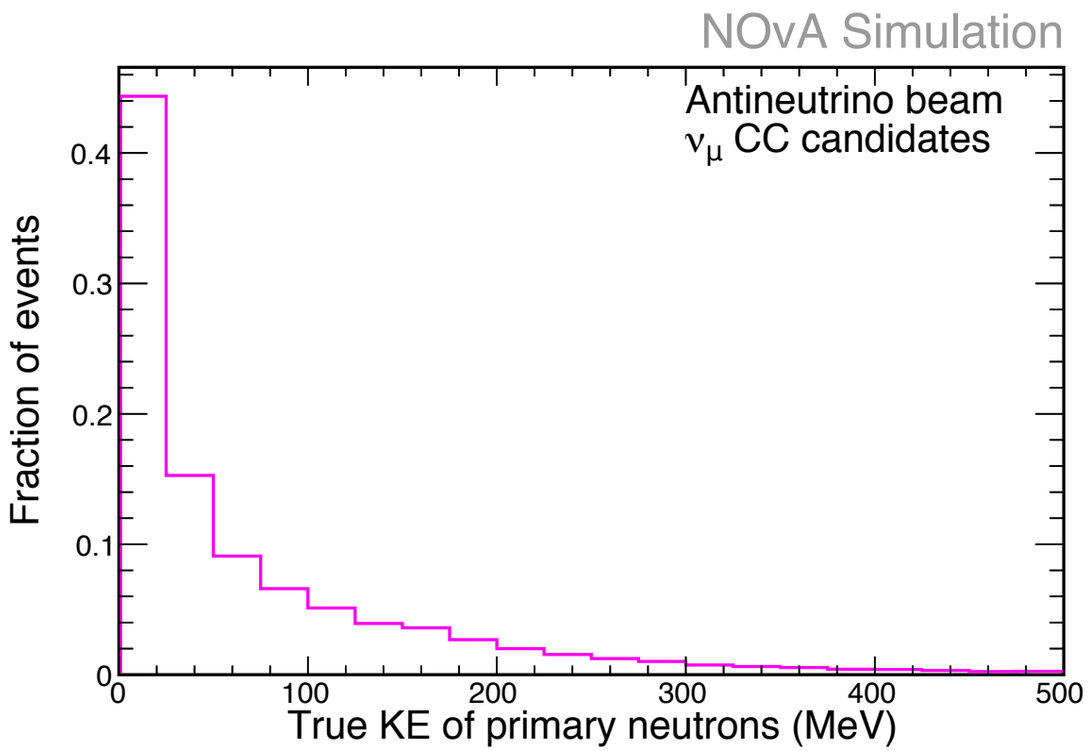
Neutrino Interaction Tuning

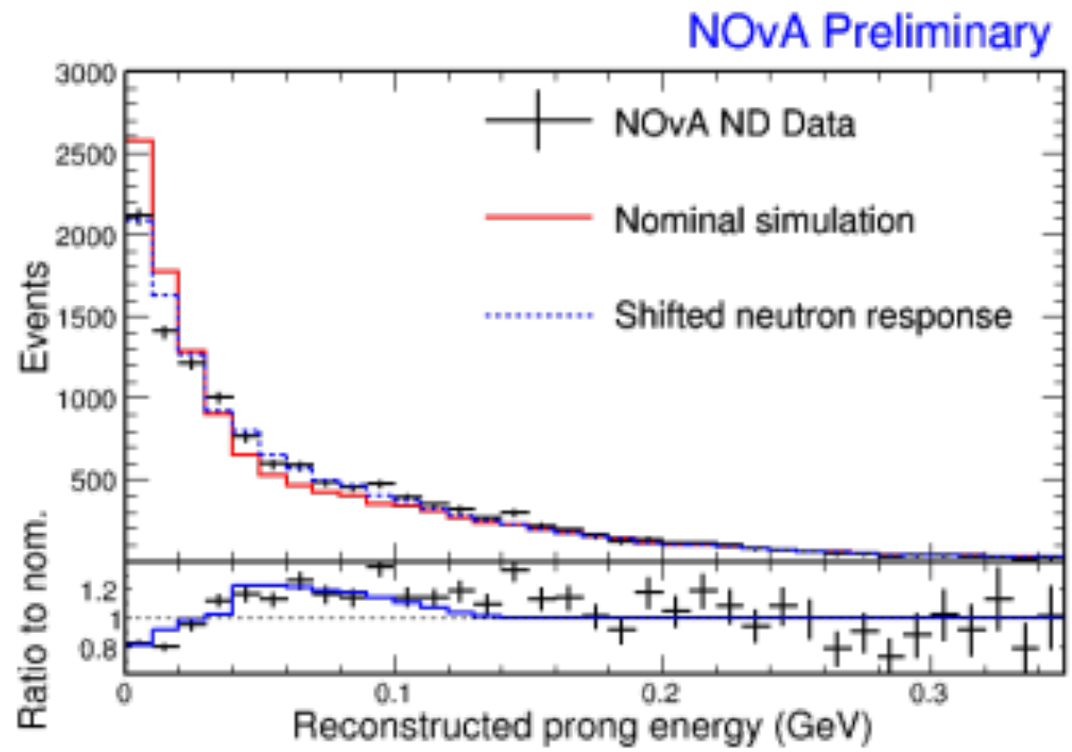
- Introduce custom tuning of GENIE "Empirical MEC" [T. Katori, AIP Conf. Proc. 1663, 030001 (2015)] based on NOvA ND data to account for multinucleon knockout (2p2h).
- This tuning procedure matches the added 2p2h component to the NOvA data excess in two-dimensional four-momentum transfer (q0,lql) space using closely-related related observables.
- The MINERvA collaboration's tuning to their data resulted in similar shape features to our assumed uncertainties.

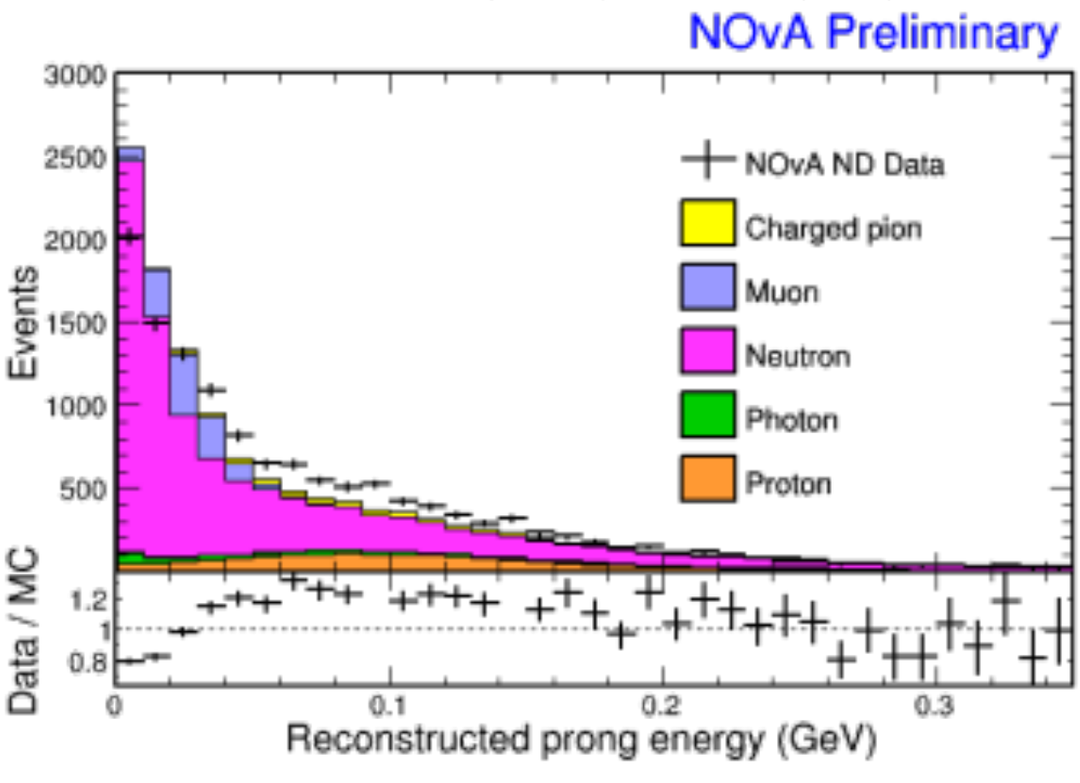




Neutrons





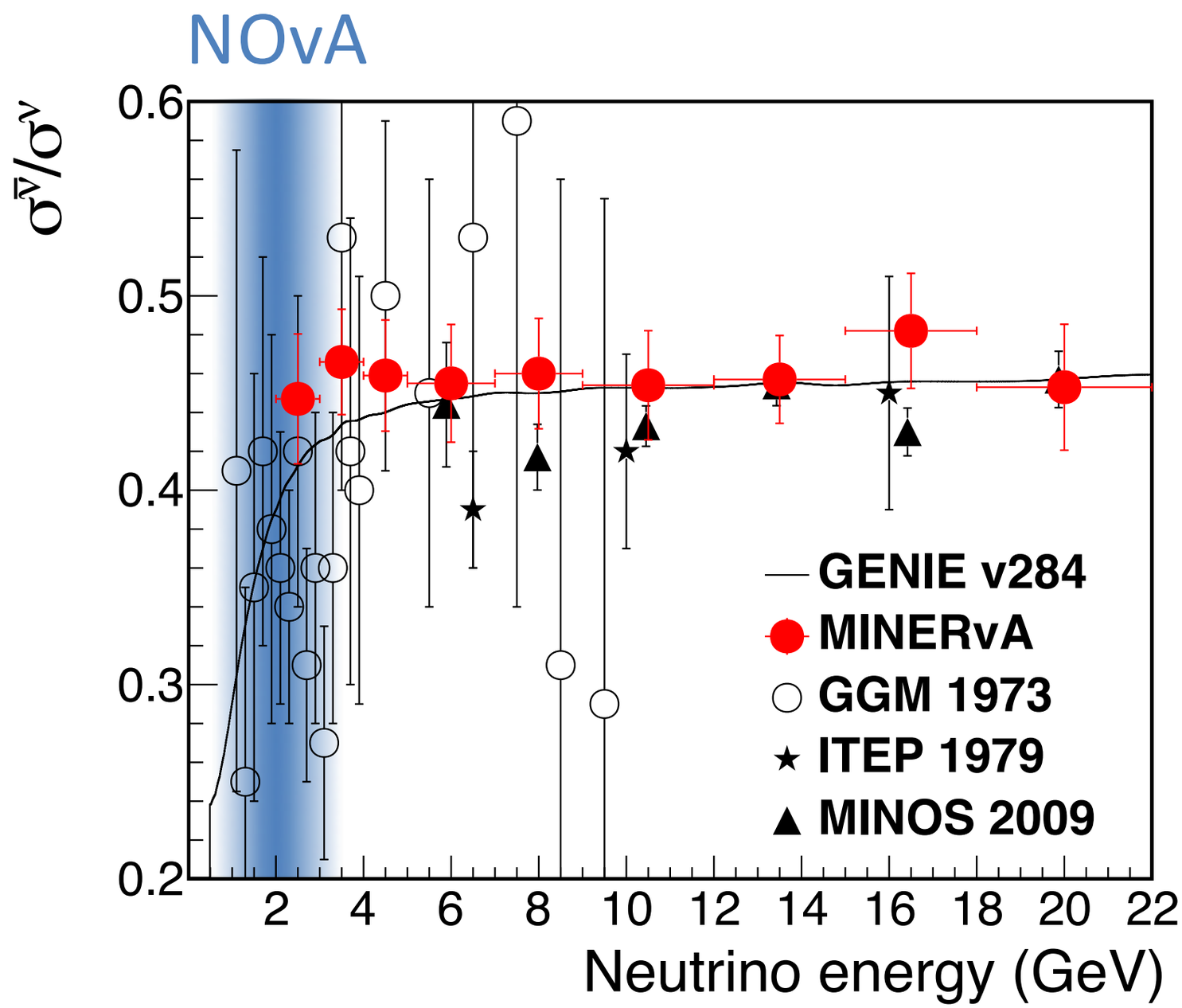


Antineutrinos have neutrons where neutrinos have protons.

Introduce systematic scaling the amount of energy deposited for some neutrons to cover low energy discrepancy

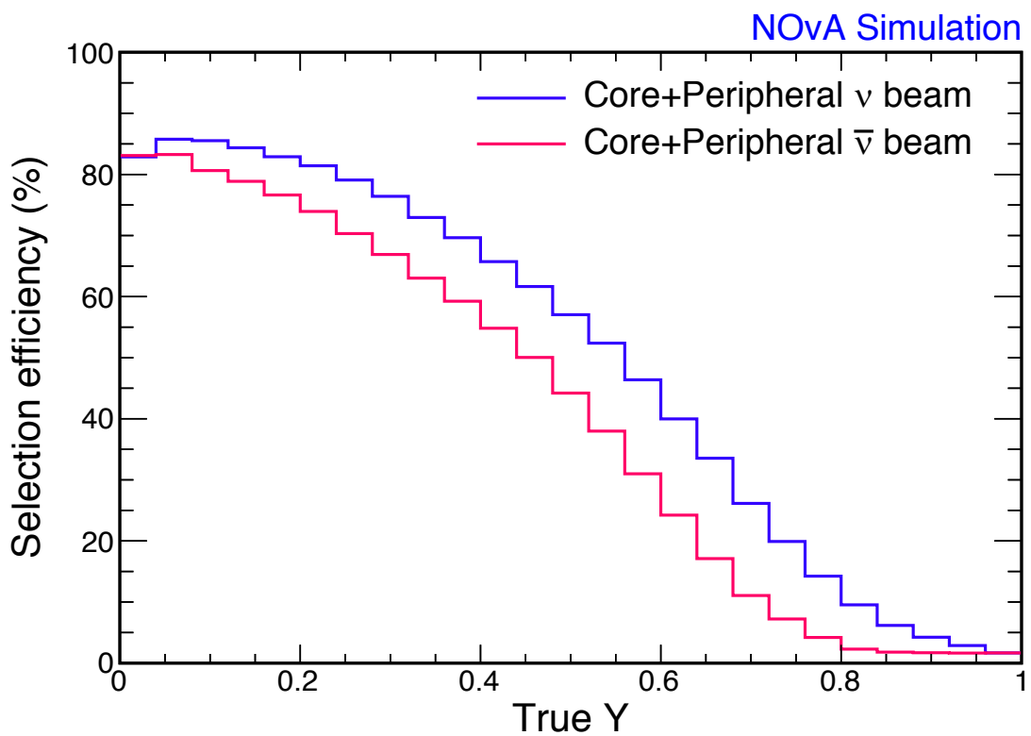
Shifts mean ν_μ energy by 1% in antineutrino beam, 0.5% in neutrino beam with negligible impact on selection efficiency

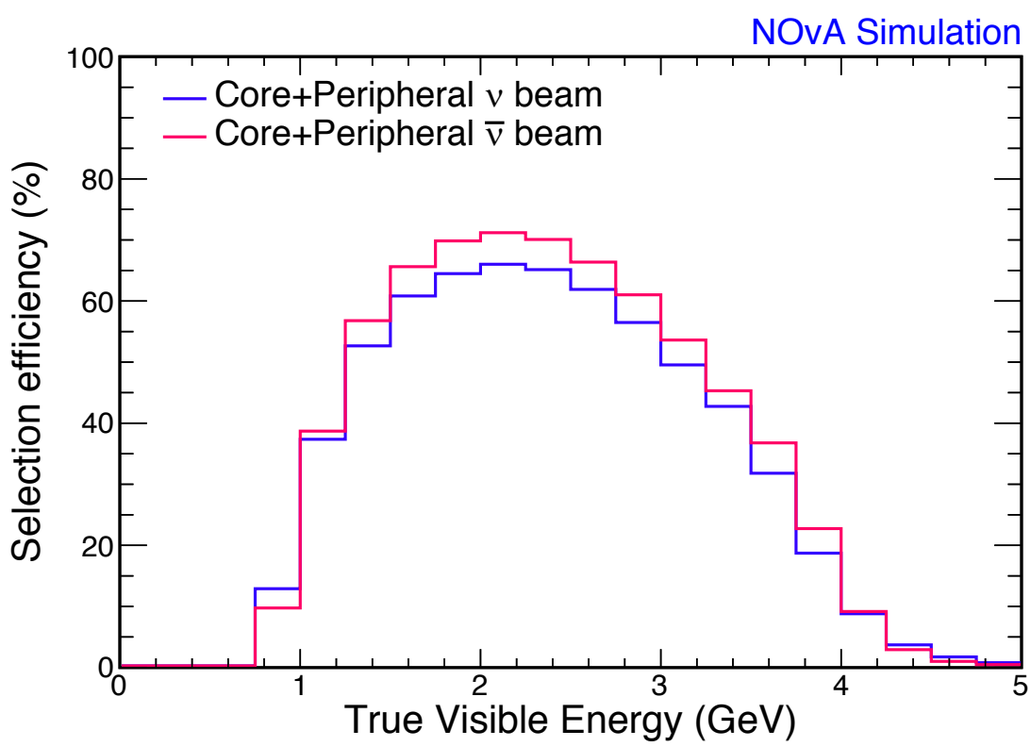
Cross section ratio

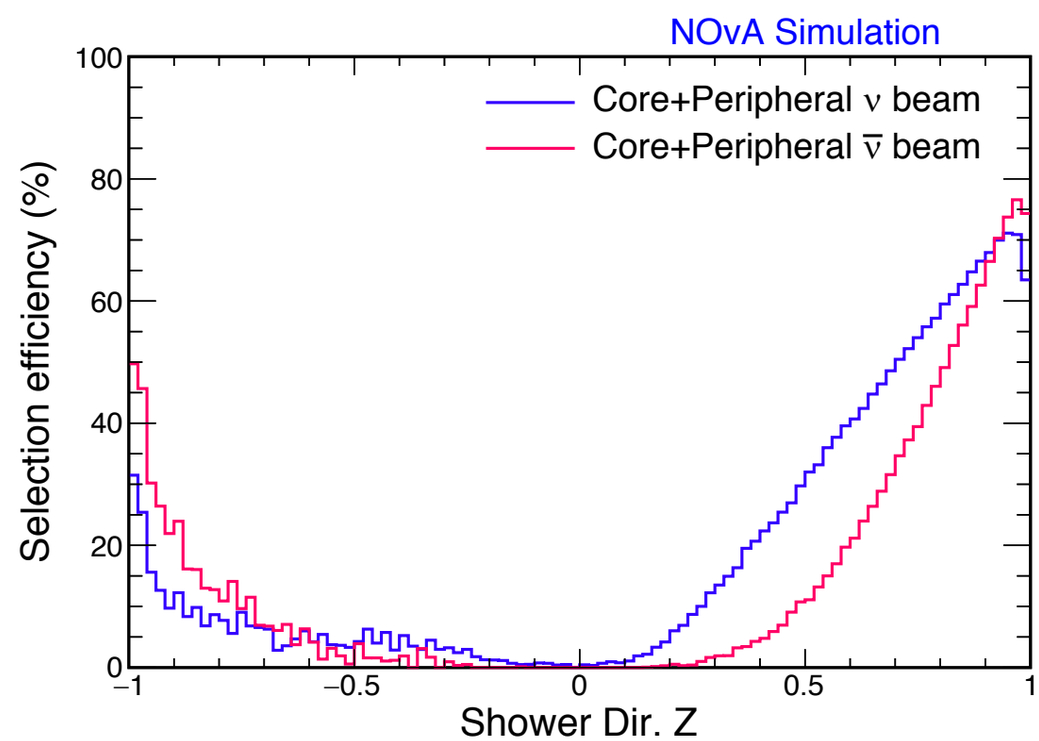


MINERvA, Phys.Rev. D95 (2017) no.7, 072009

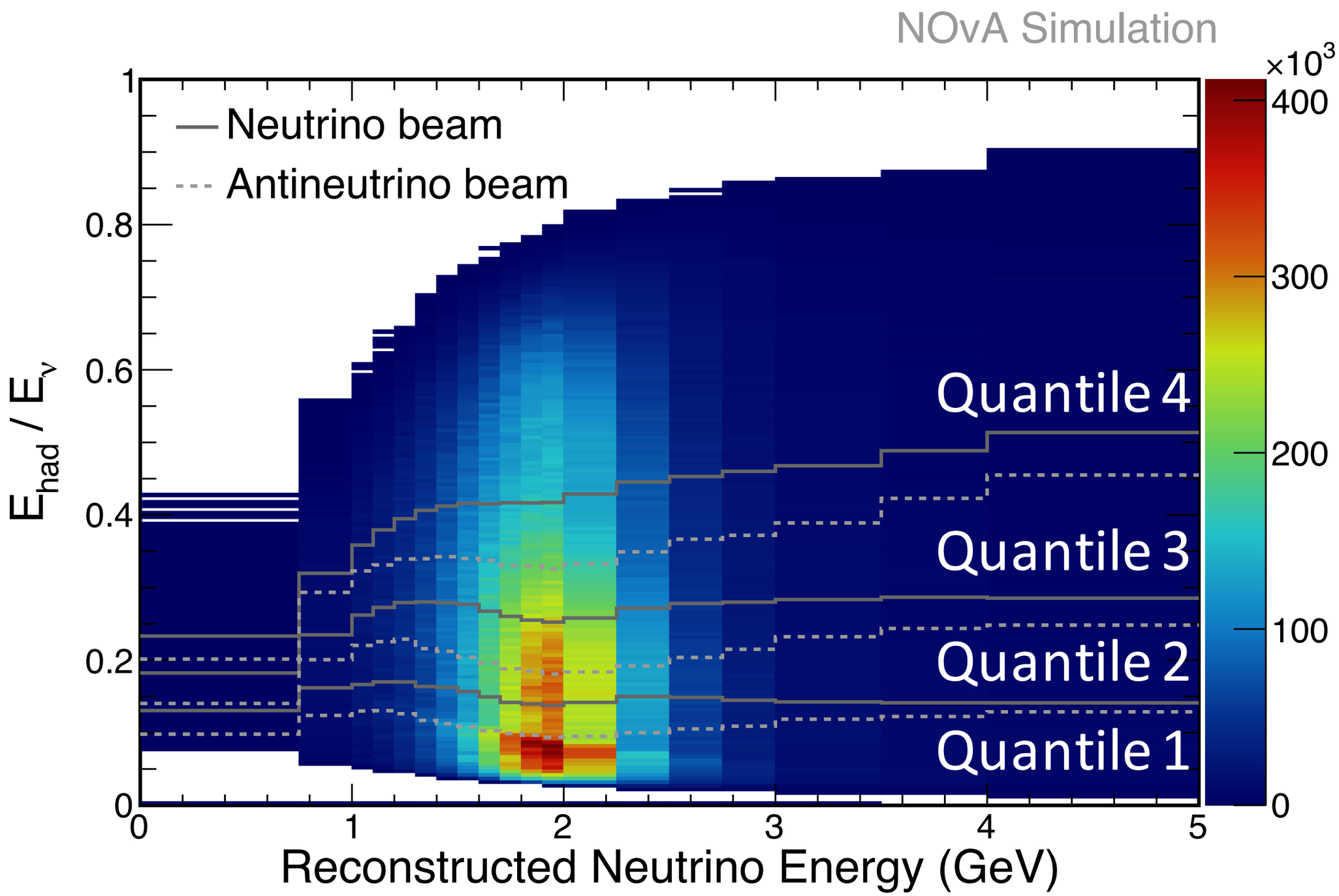
Selection Efficiencies







Resolution binning



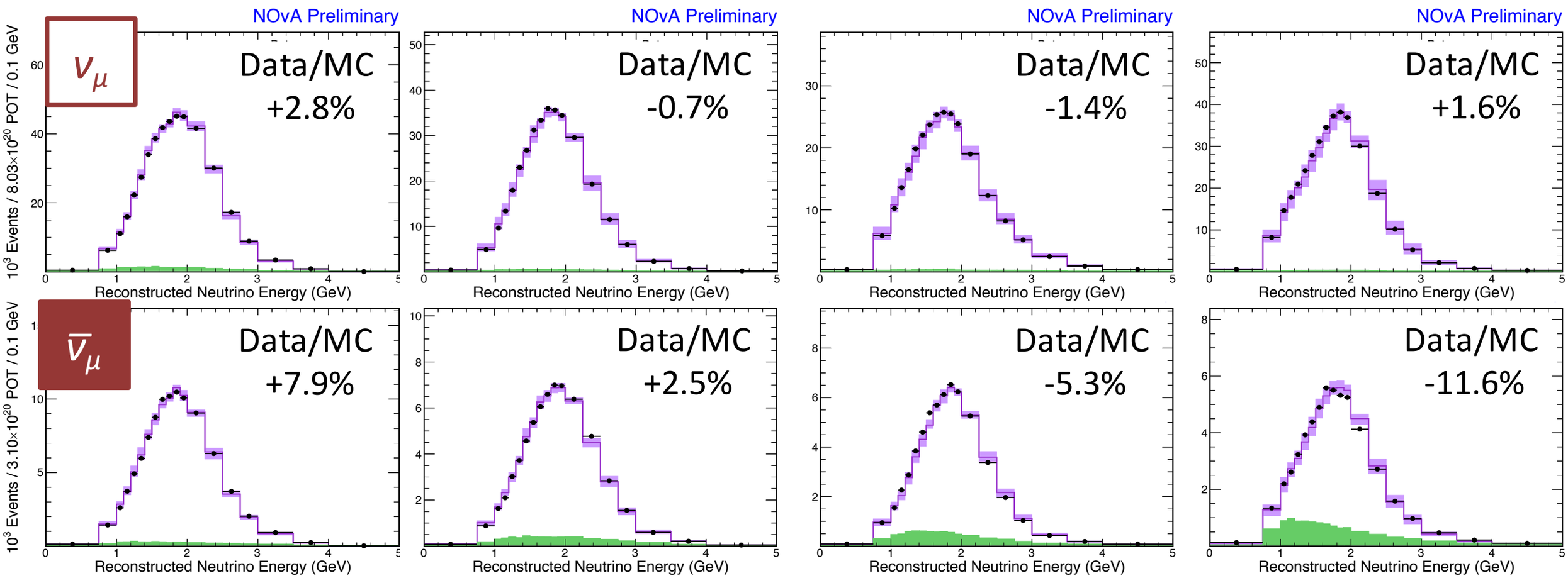
Resolution binning

Quantile 1

Best Resolution ~6%

Quantile 4

Worst Resolution ~12%



Fermilab