Recent oscillation results from NOνA

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What is NOvA

Long baseline neutrino experiment

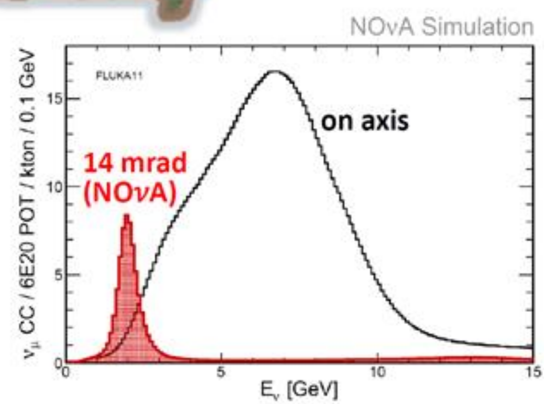
- $E \approx 2$ GeV (off-axis narrow band beam)
- L = 810 km
- Oscillations governed by Δm^2_{32} (Δm^2_{31})

NuMI beam produced at Fermilab

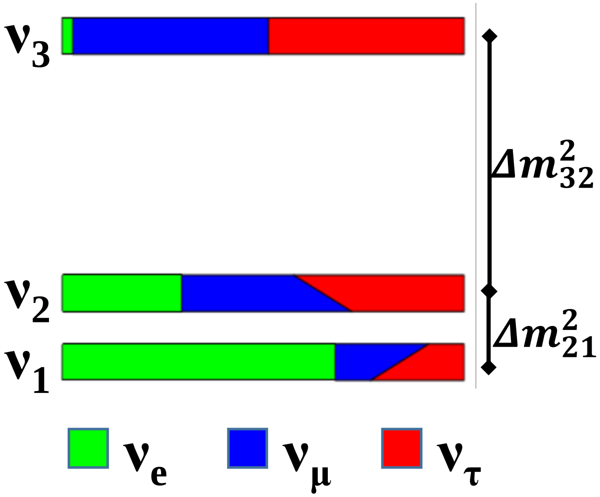
- ν_μ and $\bar{\nu}_\mu$ beam modes
  - Analyzed 8.85e20 POT with ν_μ mode
  - Analyzed 6.91e20 POT with $\bar{\nu}_\mu$ mode
- $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_x$ oscillations

Two detector experiment

- Near detector (Fermilab, IL)
  - Measure beam before oscillation
- Far Detector (Ash River, MN)
  - Measure oscillated beam



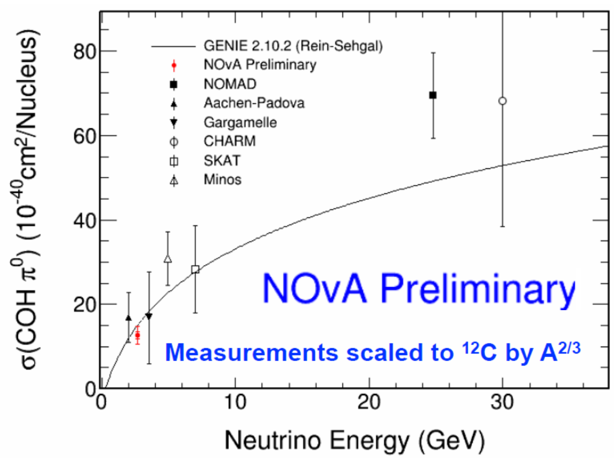
Physics Goals



Long baseline neutrino oscillation measurements

- **ν_μ CC disappearance**
- **ν_e CC appearance** (long baseline +30% matter effect)
  - Sensitive to: θ_{23}, δ_{CP}, Δm^2_{32} (*Mass Hierarchy*)
- **NC disappearance**
  - Sensitive to Sterile Neutrinos: θ_{24}, θ_{34}, Δm^2_{41}

NC Coherent Pion Production Measurement



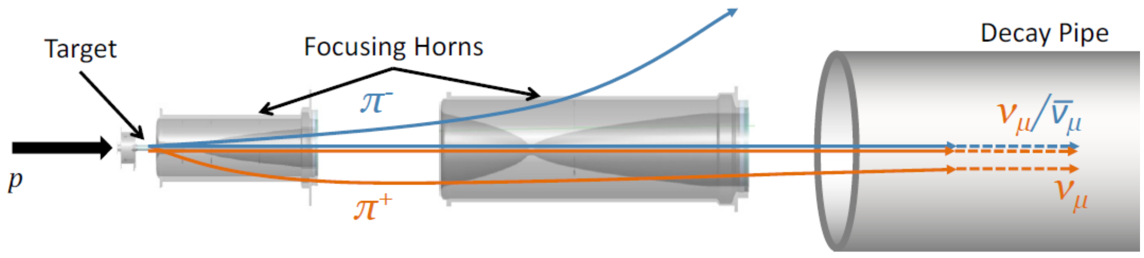
$\sigma = 14.0 \pm 0.9(\text{stat.}) \pm 2.1(\text{syst.}) \times 10^{-40} \text{cm}^2/\text{nucleus}$

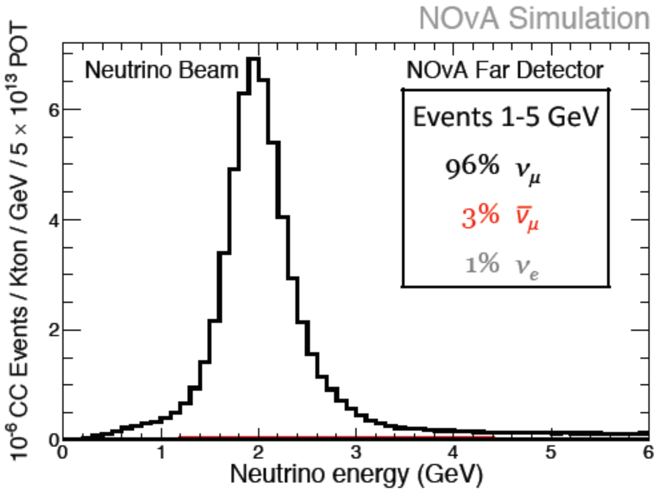
Non-oscillation Measurements

- **Near Detector cross sections measurements**
- **Supernova detection**
- **Exotic phenomena**
  - Monopoles, neutrino magnetic moment, etc

NuMI Beam

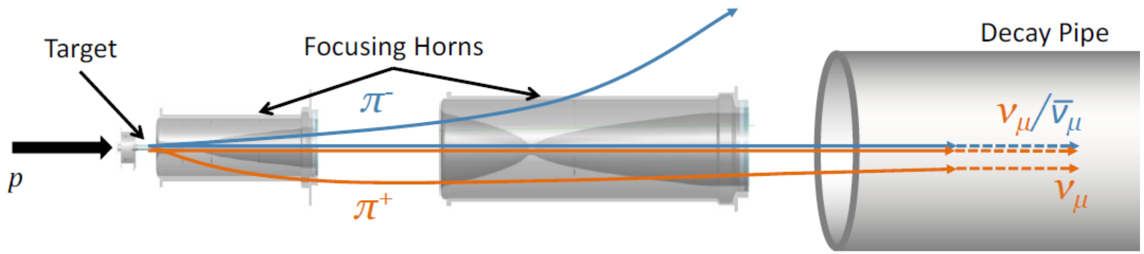
Neutrino Mode

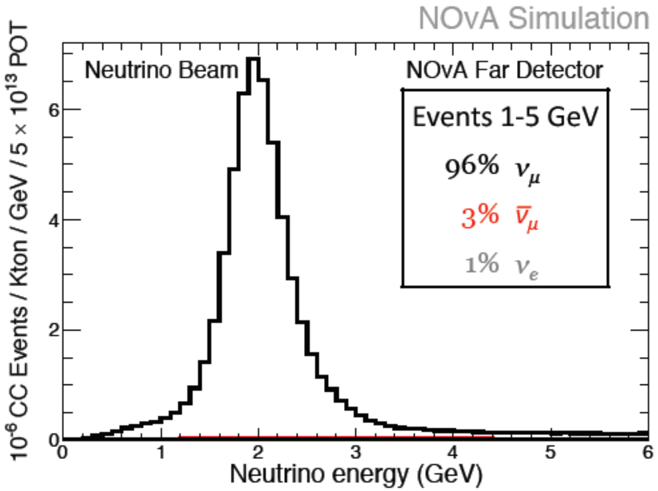




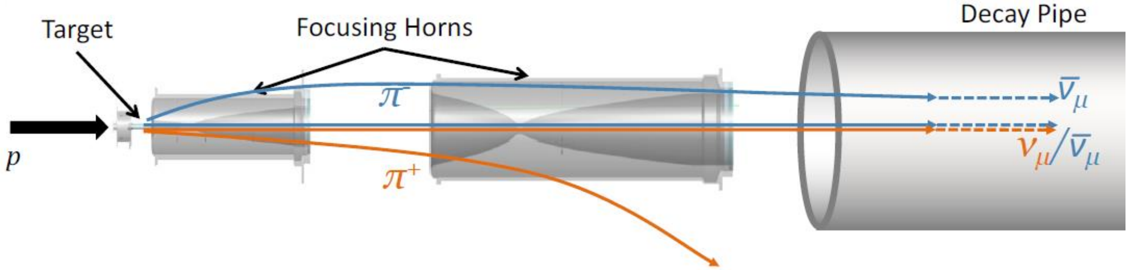
NuMI Beam

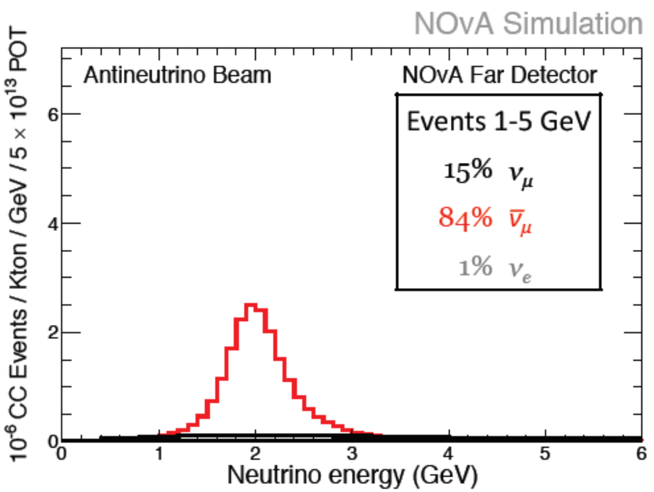
Neutrino Mode





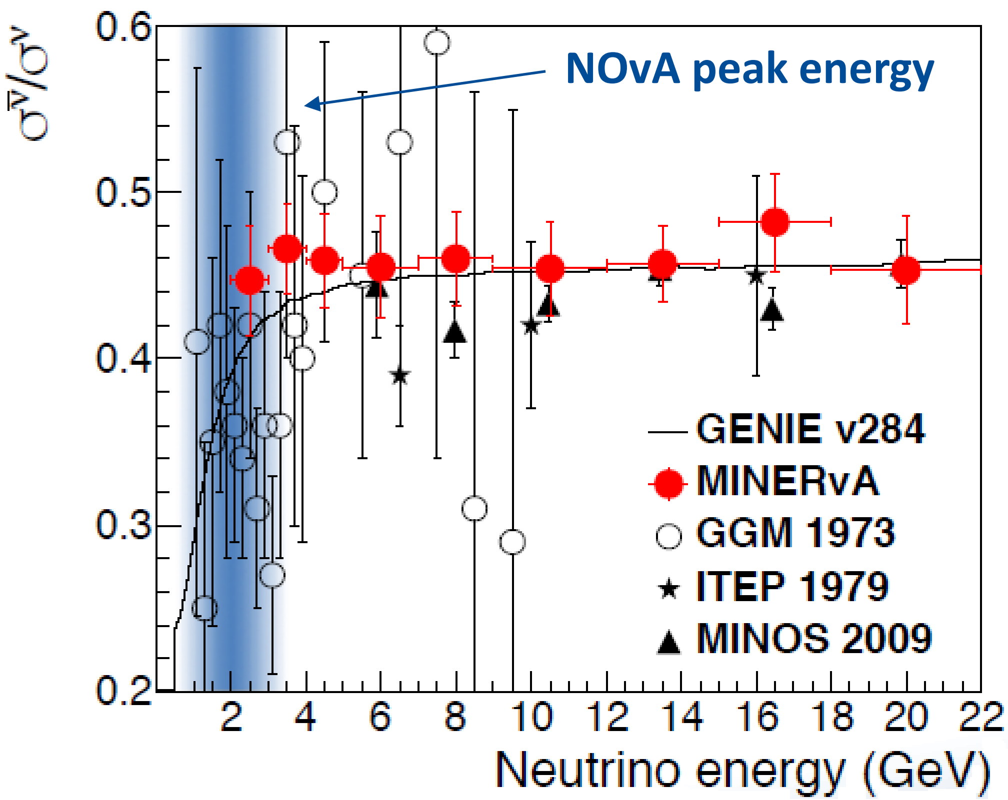
Antineutrino Mode

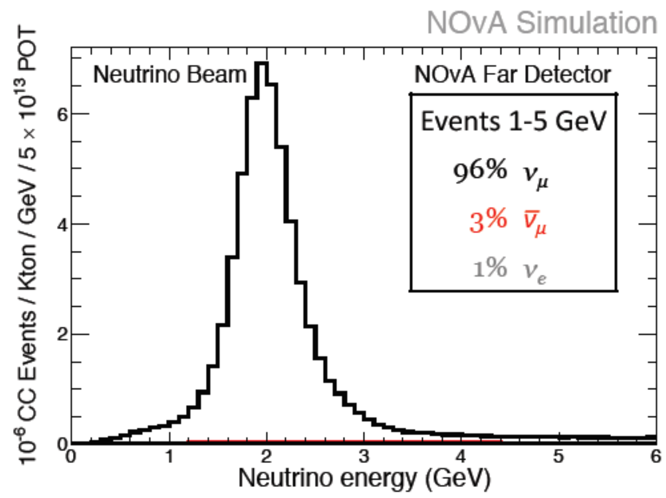


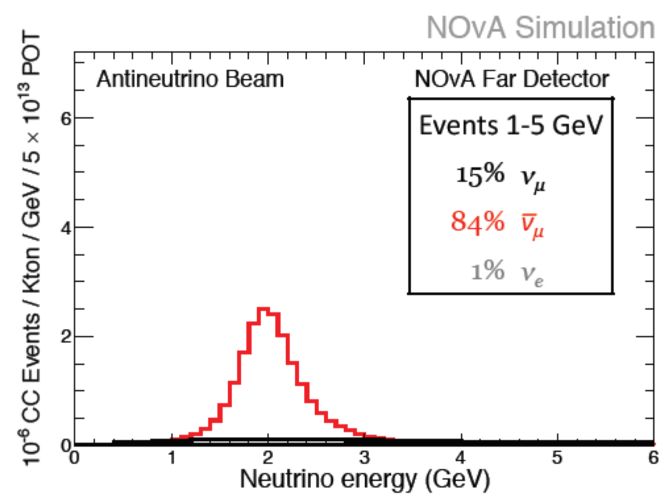


NuMI Beam

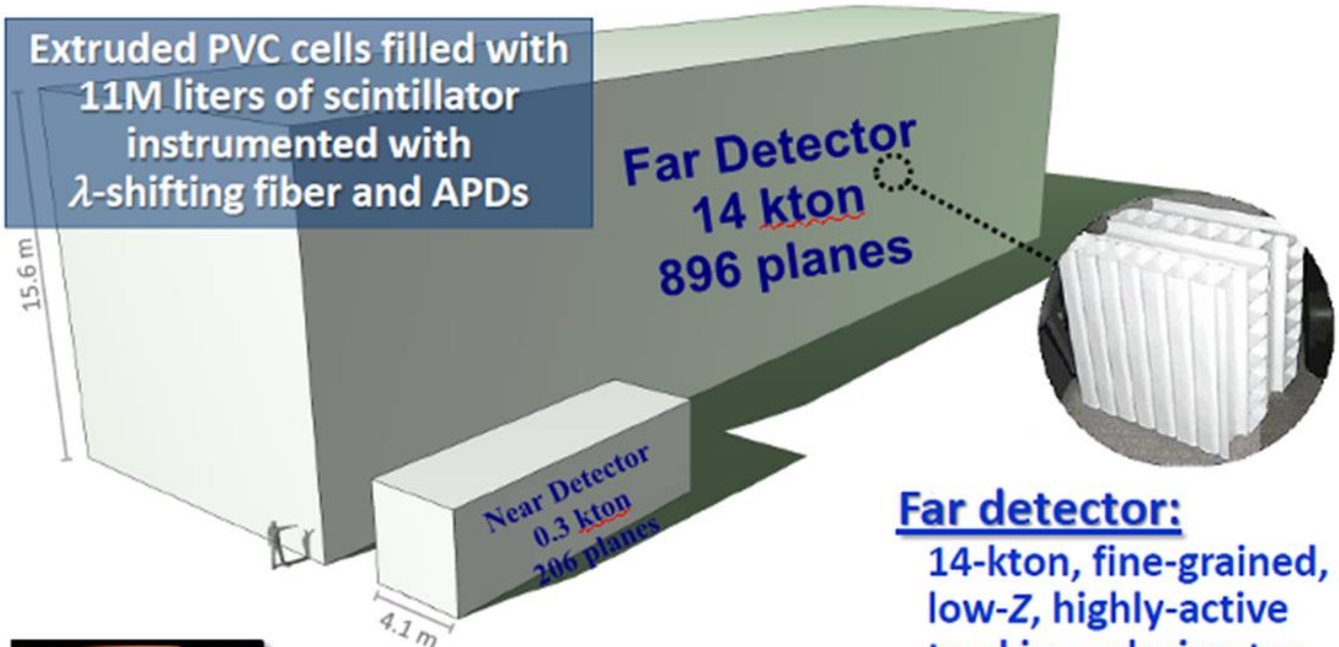
For NOvA energies, the antineutrino cross-section is ~2.8 times lower than the neutrino



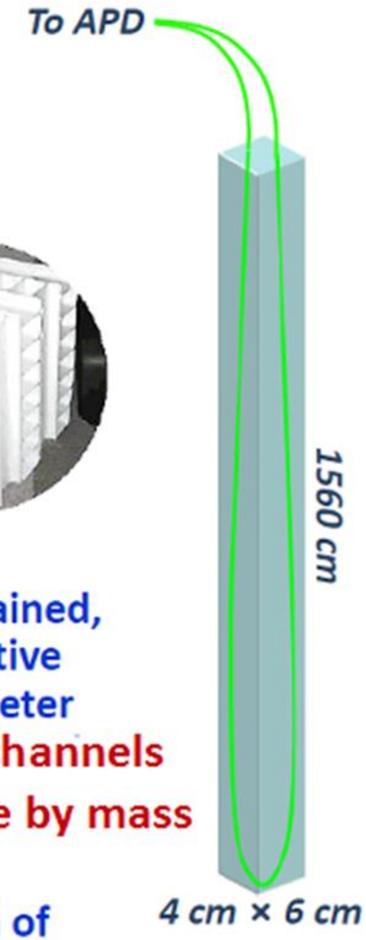




Two Detector Experiment



A NOνA cell



Far detector:

14-kton, fine-grained, low-Z, highly-active tracking calorimeter

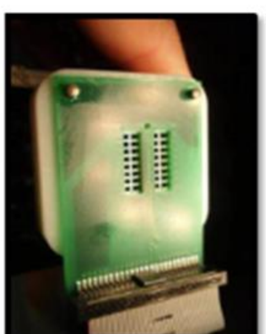
340, 000 channels

77% active by mass

Near detector:

0.3-kton version of the same

18, 000 channels

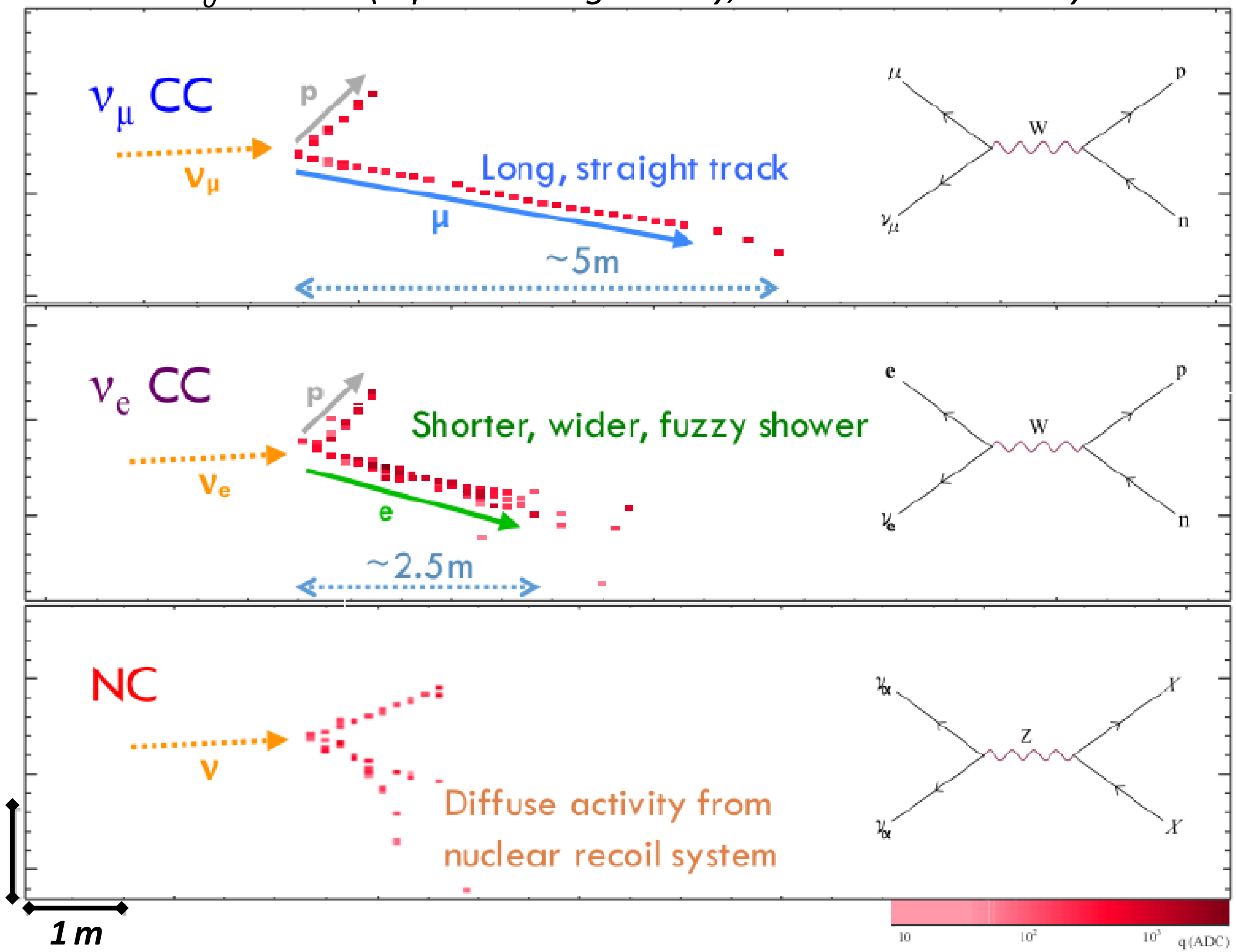


32-pixel APD ←

Fiber pairs from 32 cells →

Event Topologies

X_0 = 38 cm (6 planes longitudally, 10 cells transversely



Event Selection

Events classified with Convolutional Visual Network (CVN)

- A deep learning algorithm similar to image recognition software
  - Cells are like pixels and the energy depositions are like colors
  - Filters pick out event features

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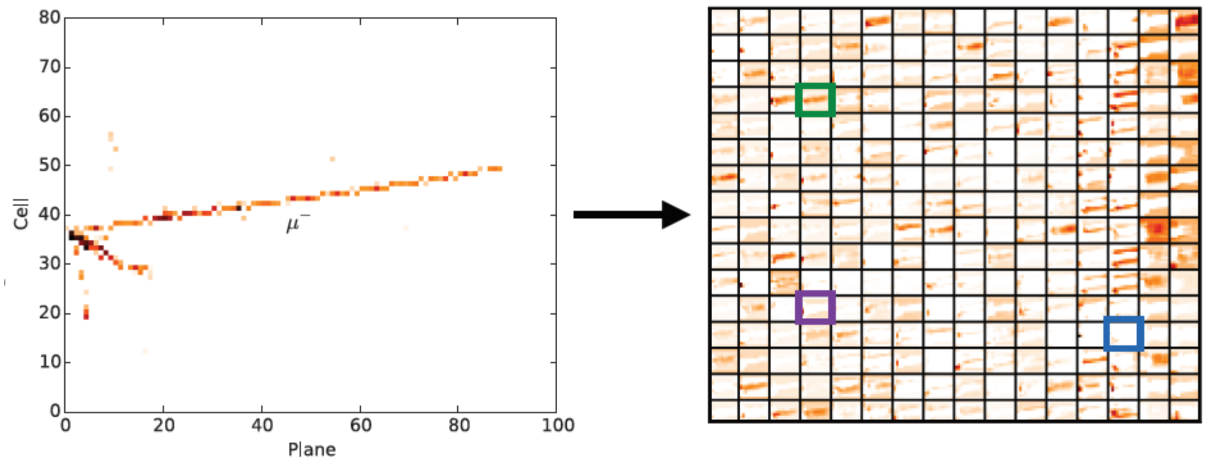


One algorithm classifies: 1) ν_μ CC 2) ν_e CC 3) NC 4) Cosmic

More selection criteria

Data Quality, preselection, containment, and cosmic rejection

- e.g. min number hits, directionality cuts, distance from detector edges, etc
- Reduces cosmic background from $\sim 10^6$ events to less than 10 events (CVN does a lot too)
- Analysis specific

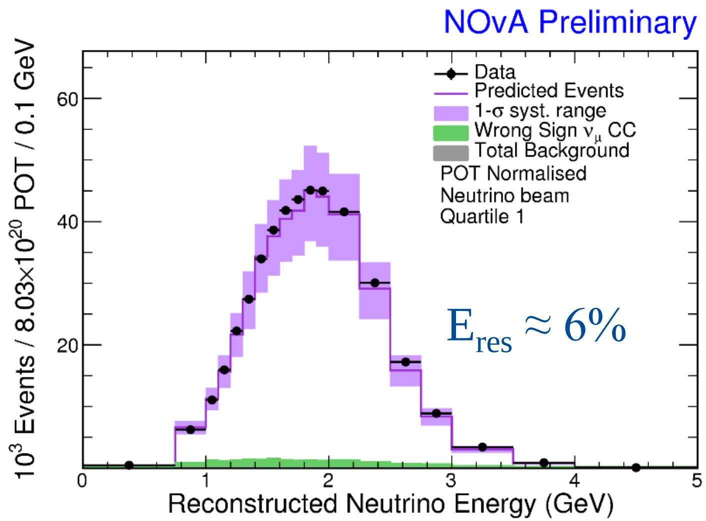
ν_μ disappearance analysis

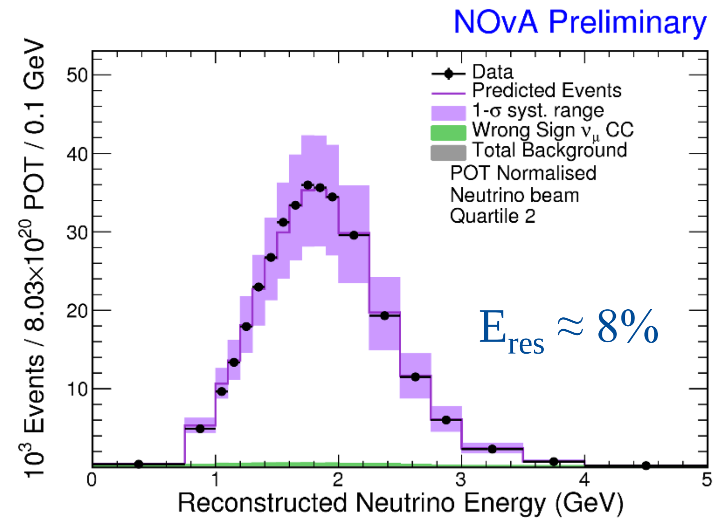
- Additional muon track ID based on kNN (track length, dE/dx, scattering, quality)
- Events separated into 4 subsamples by hadronic energy fraction
  - Lower had E fraction $\rightarrow$ fraction has better energy resolution and purity

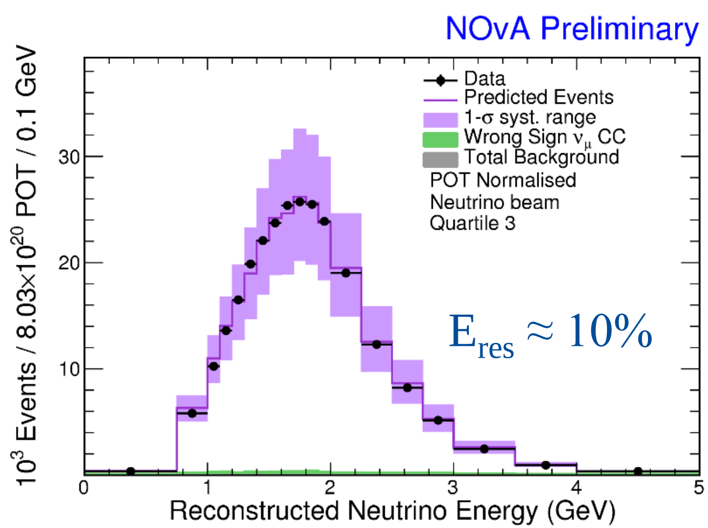
ν_e appearance analysis

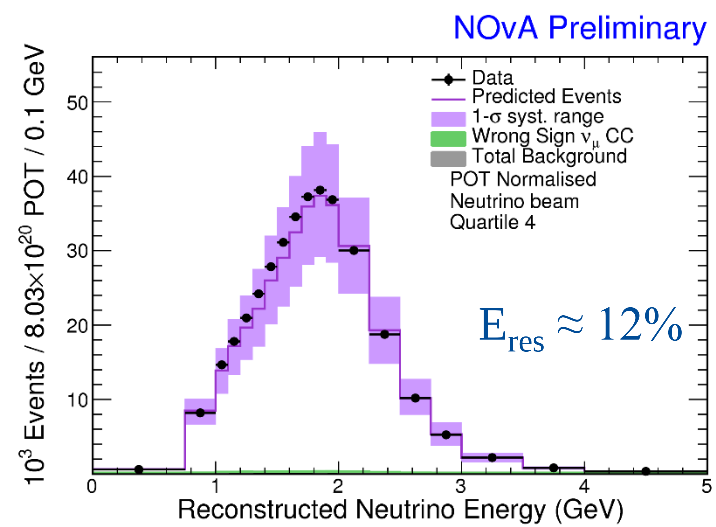
- Reclaim events that fail primary (core) cuts by reexamining with alternate cosmic cuts
  - Forms a peripheral sample
- Separate core events into 2 subsamples by CVN value
  - Higher CVN $\rightarrow$ better purity

ND Selection - ν_μ CC

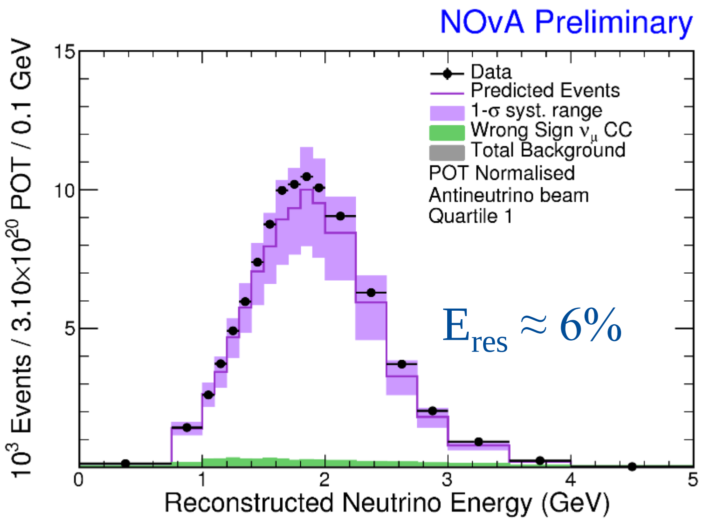


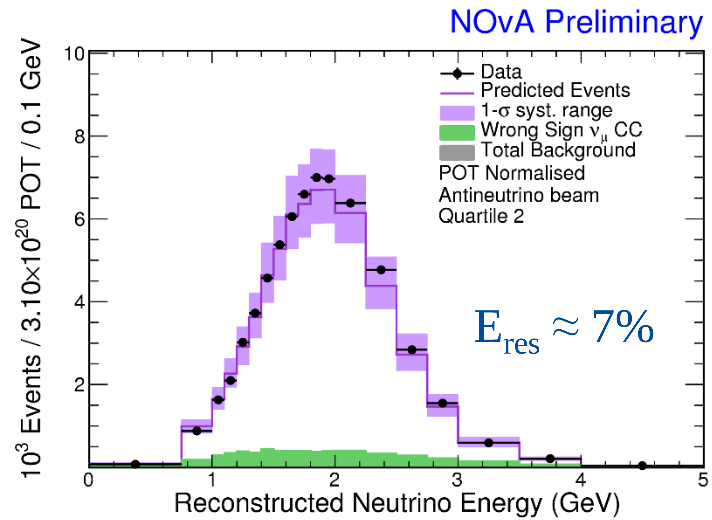


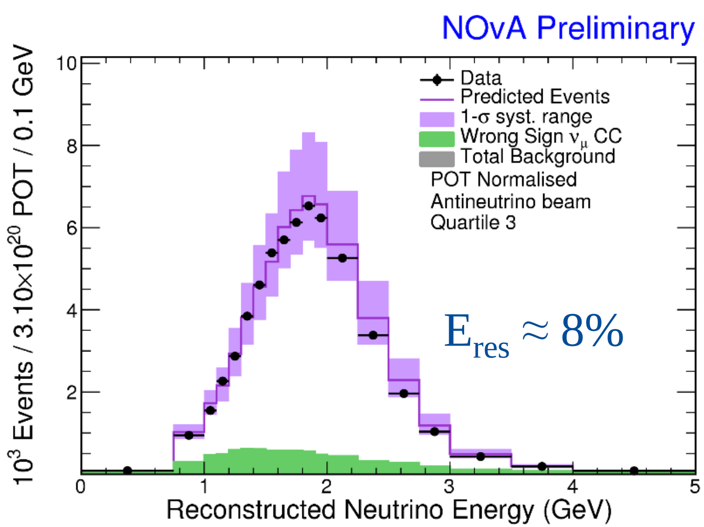


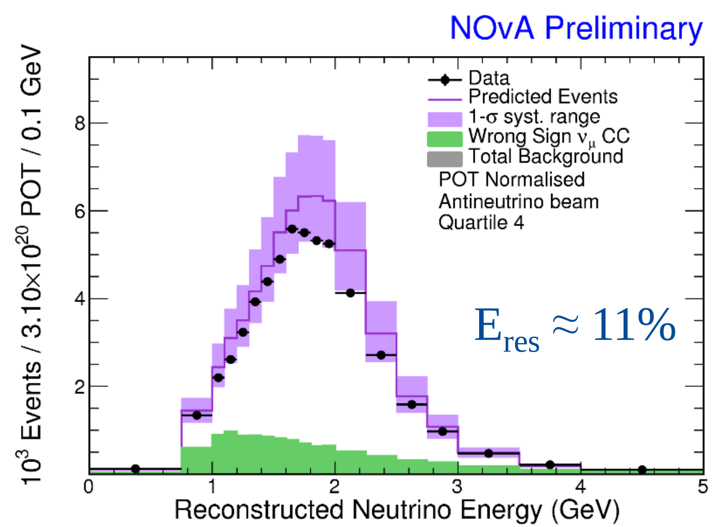


ND Selection - $\bar{\nu}_\mu$ CC

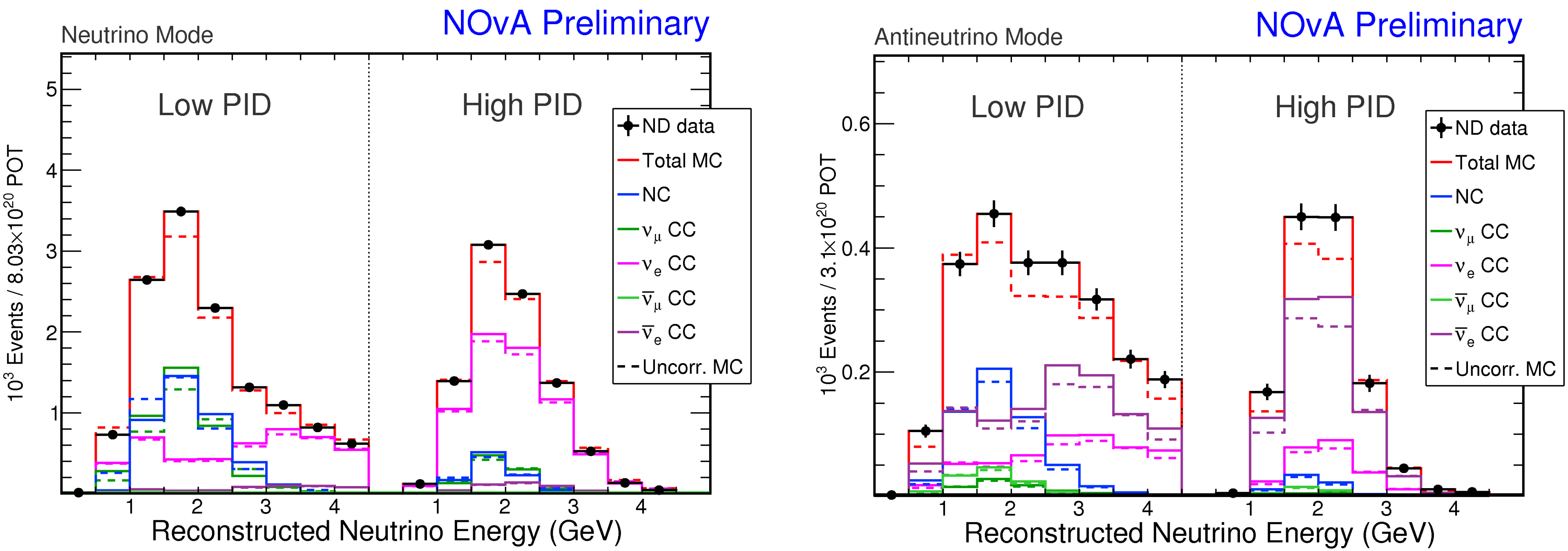








ND Selection - $\nu_e + \bar{\nu}_e$ CC

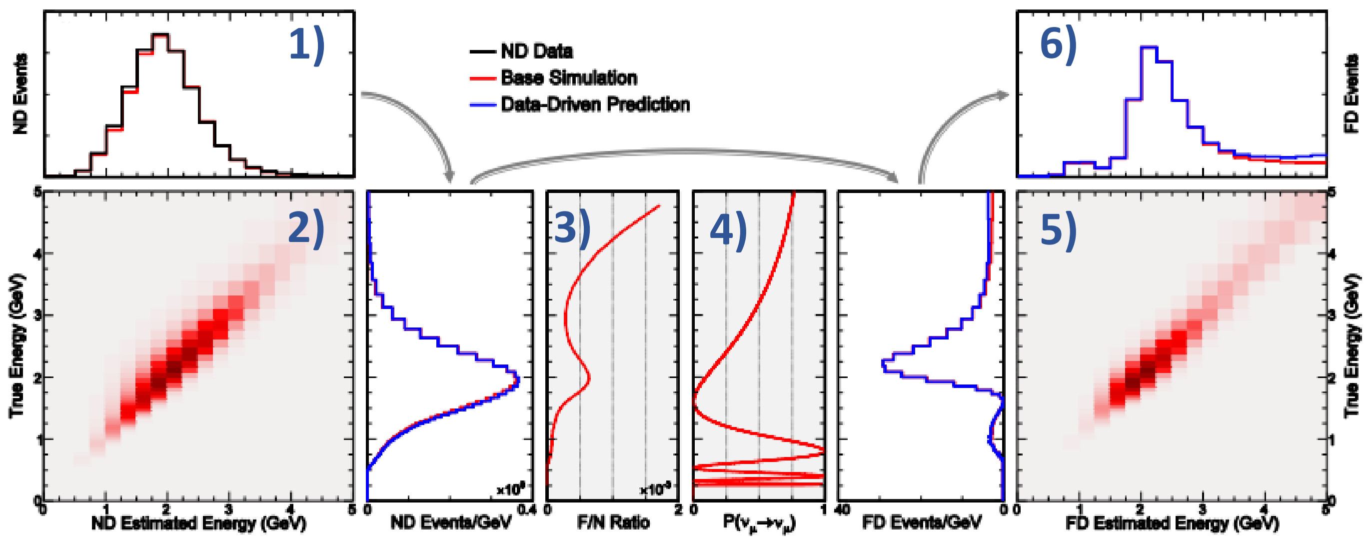


Near detector sample is Far Detector appearance background sample

ν_μ-CC, NC, and intrinsic beam ν_e-CC extrapolate differently to FD

Extrapolation

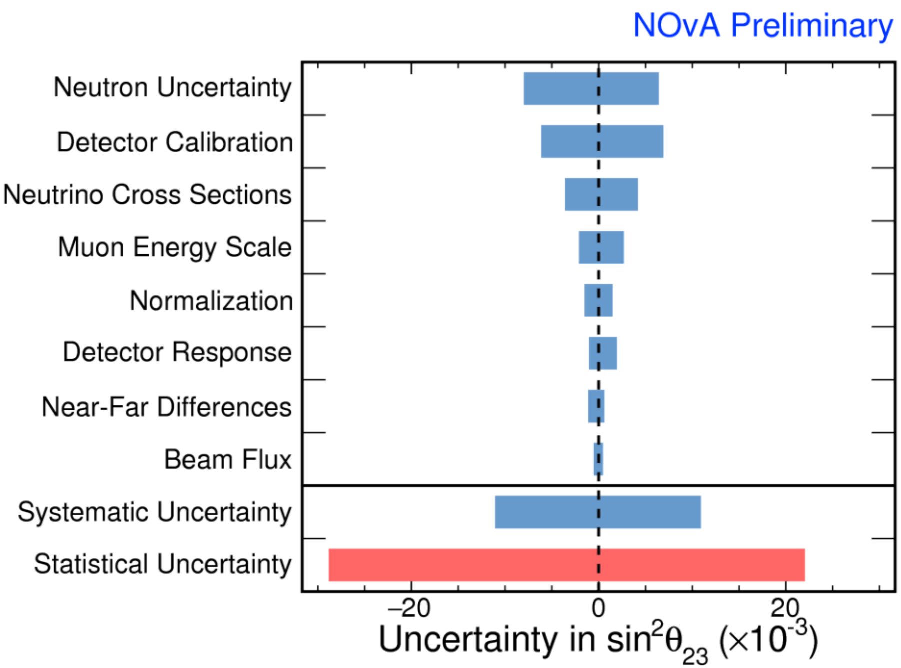
1) Select events in ND (use data)
2) Map ND reco E to true E (use simulation)
3) Apply ratio of FD events to ND events in bins of true E (use simulation)
    Takes into account differences between two detectors
4) Apply oscillation probability on FD true E events (use simulation)
5) Map FD true E to reco E (use simulation)
6) Oscillated FD prediction

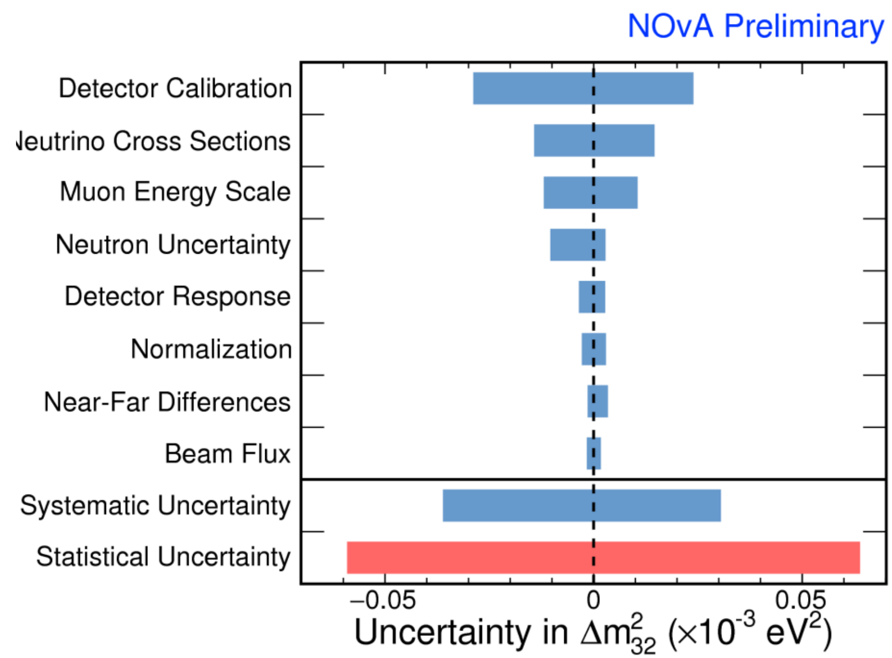


Don't need to separately measure flux, cross-section, efficiencies, etc in ND

Systematics accounted for by altering simulation at steps 2, 3, 4, and 5

Systematics - $\nu_\mu + \bar{\nu}_\mu$ CC

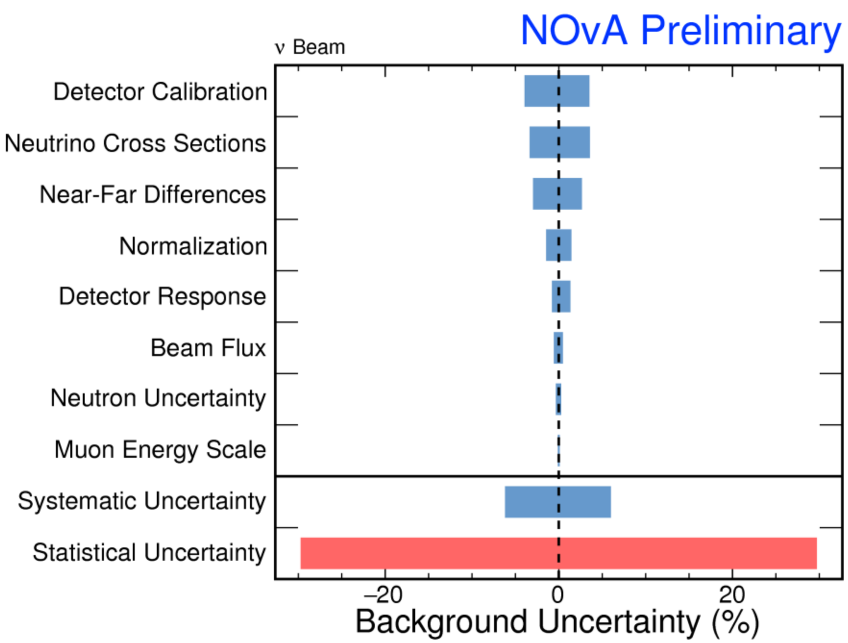


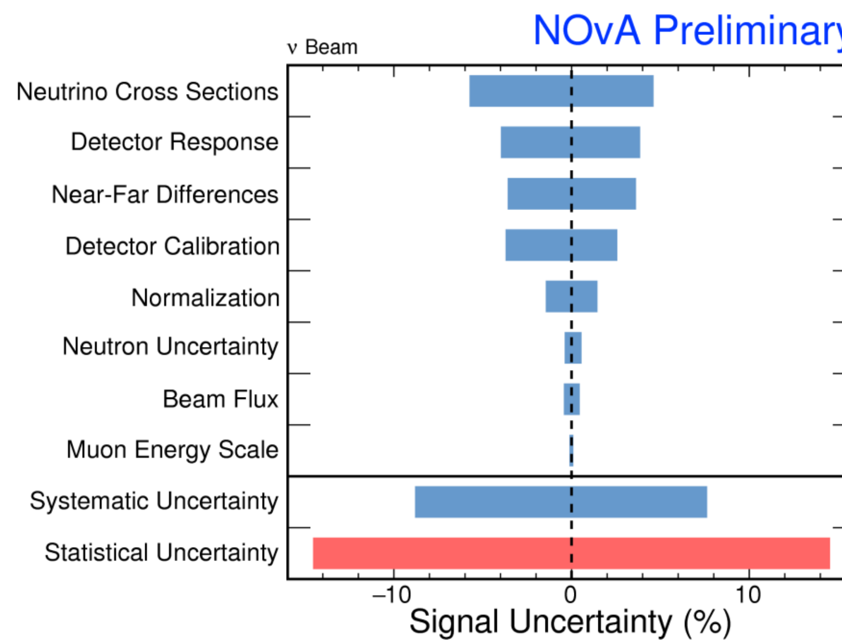


Statistics Limited

Dominant systematics related to neutron modeling, calorimetric energy calibration, and cross sections

Systematics - ν_e CC

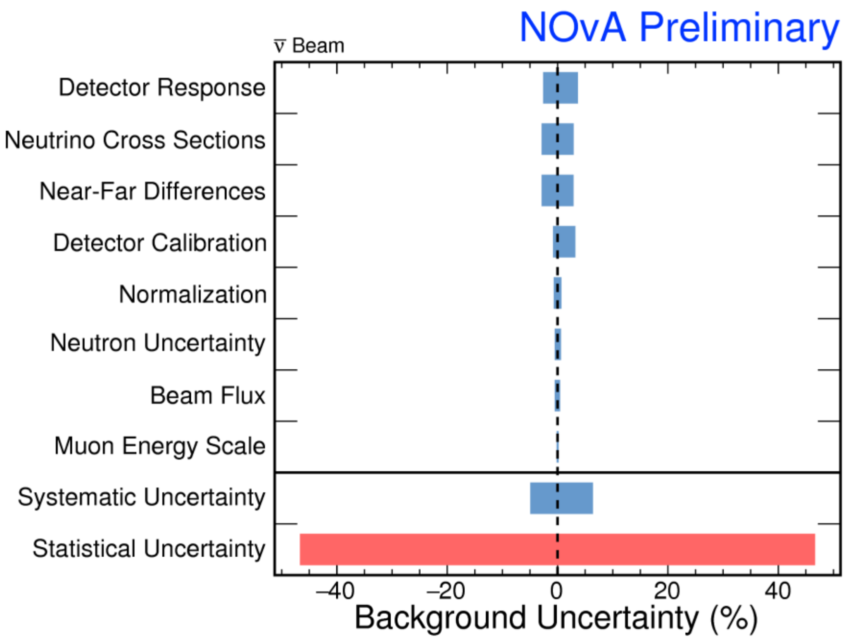


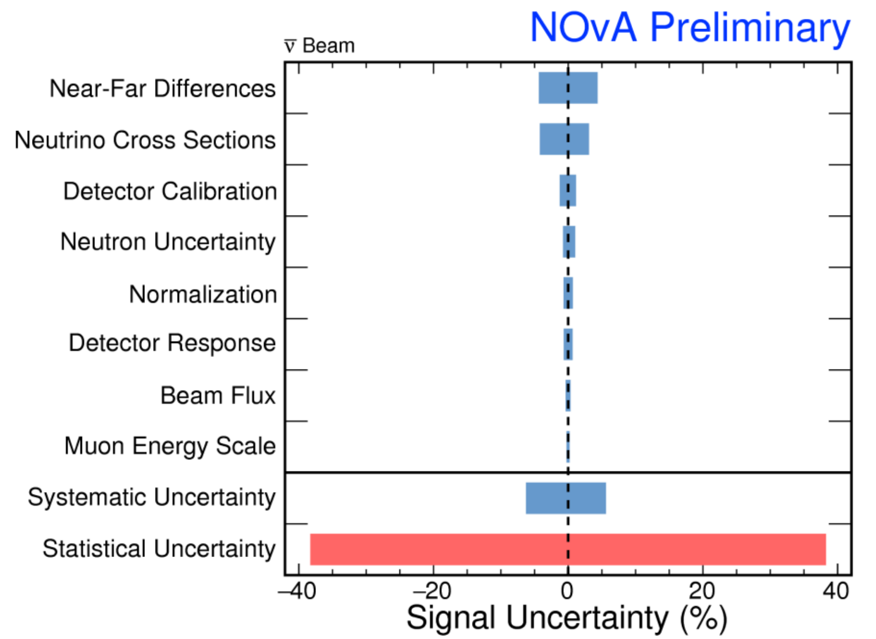


Statistics Limited

Dominant systematics related to cross sections and calorimetric energy calibration

Systematics - $\bar{\nu}_e$ CC



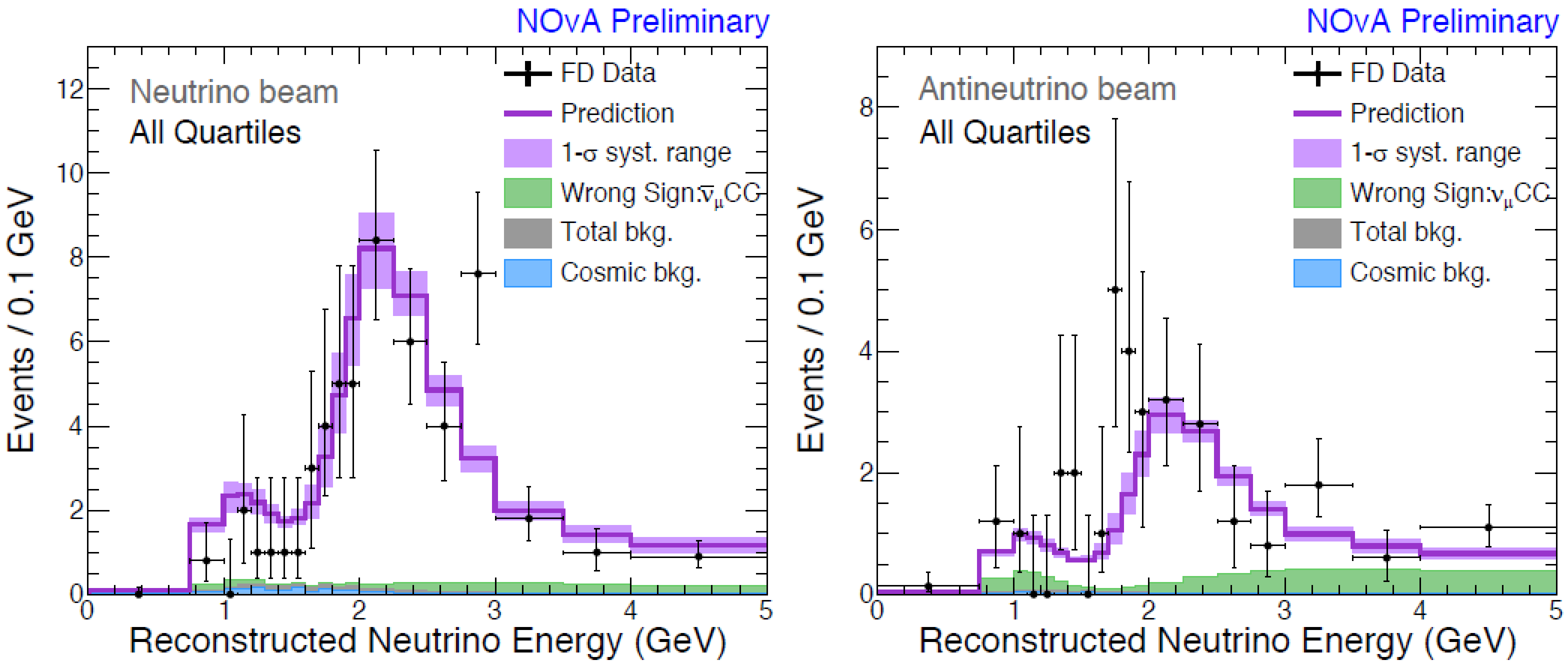


Statistics Limited

Results

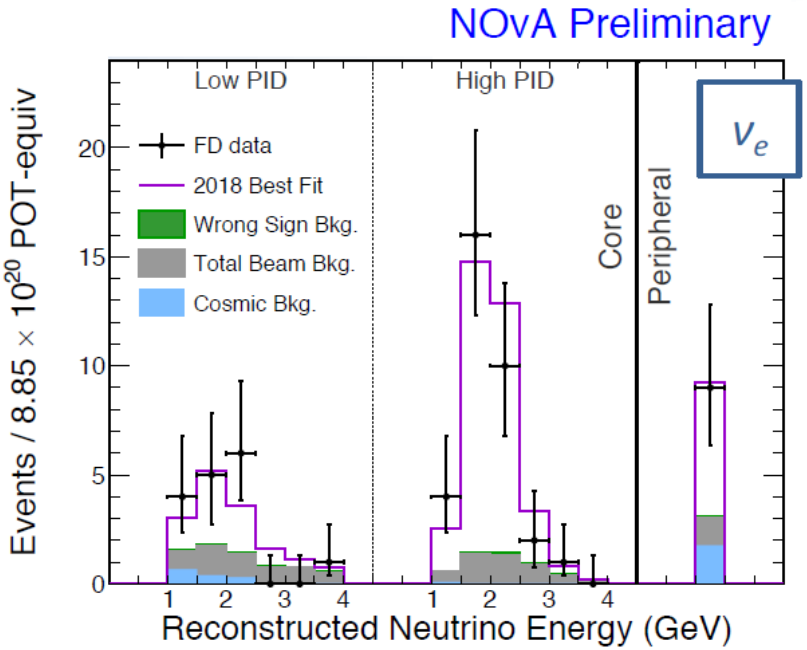
ν_μ CC Disappearance Results

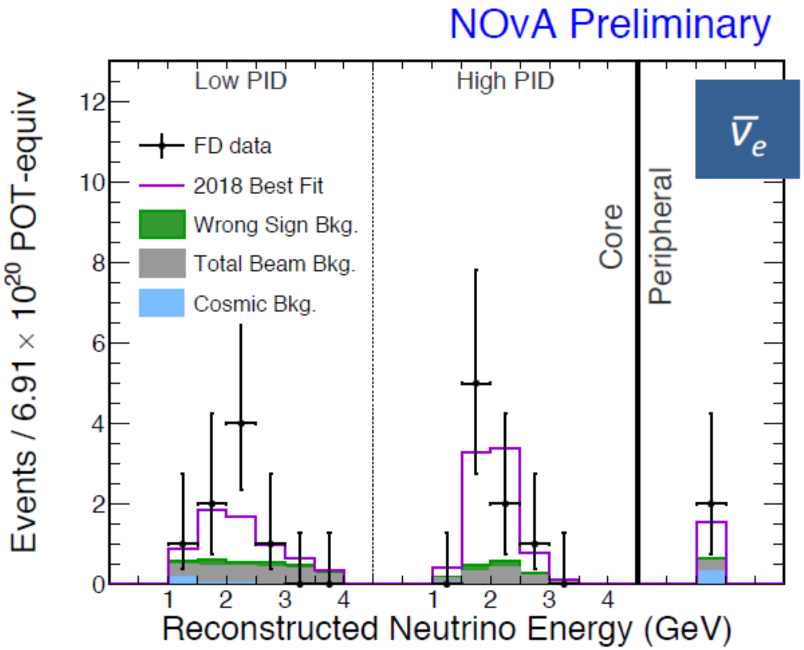
	Total Observed	Best Fit Prediction	Total Background	Cosmic Background	Beam Background
Neutrino Mode	113	121	3.3	2.1	1.2
Antineutrino Mode	65	50	1.1	0.5	0.6



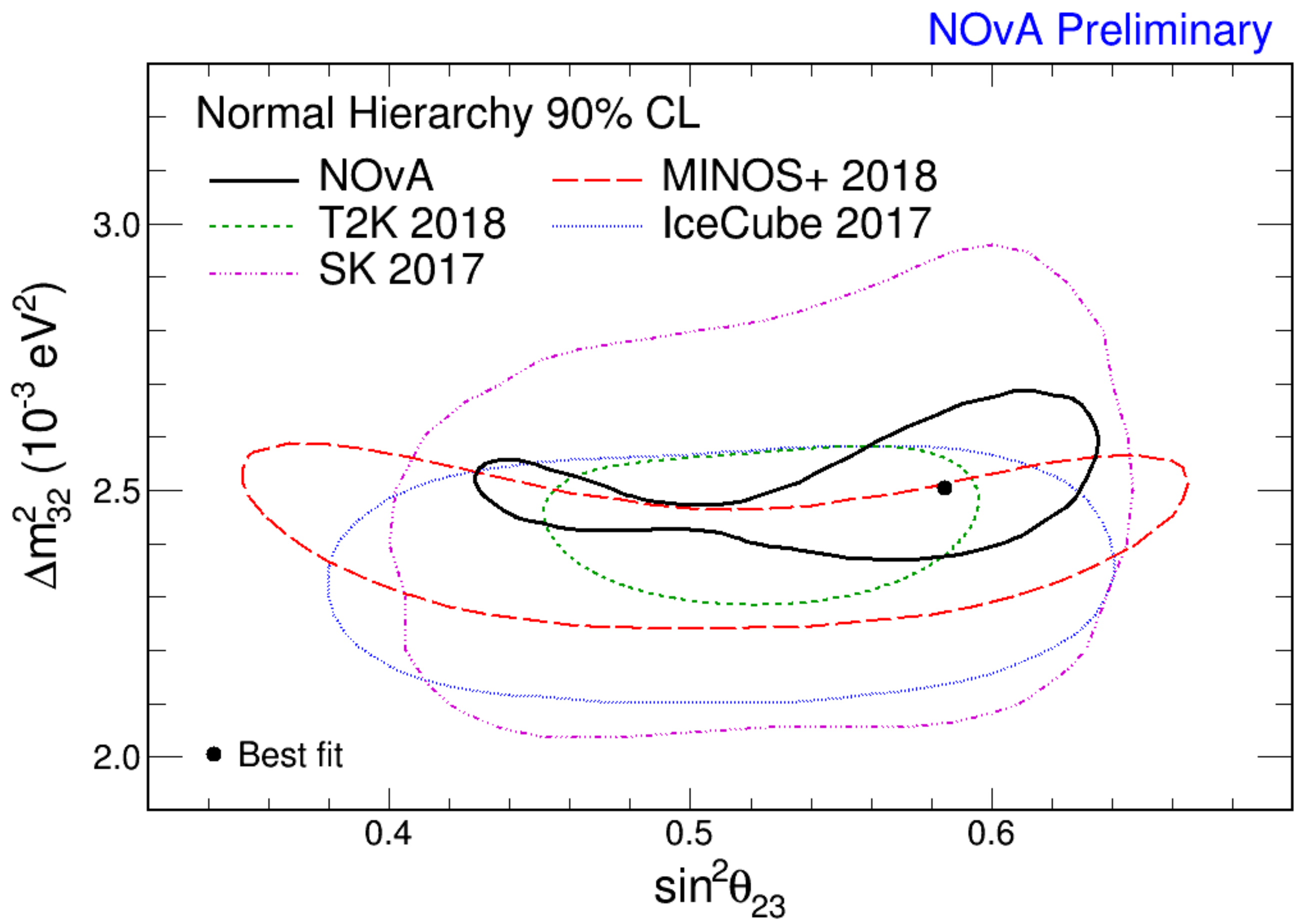
ν_e CC Appearance Results

	Total Observed	Best Fit Prediction	Wrong Sign	Cosmic Background	Beam Background
Neutrino Mode	58	59	0.7	3.3	11.1
Antineutrino Mode	18	15.9	1.1	0.7	3.5





Joint Results

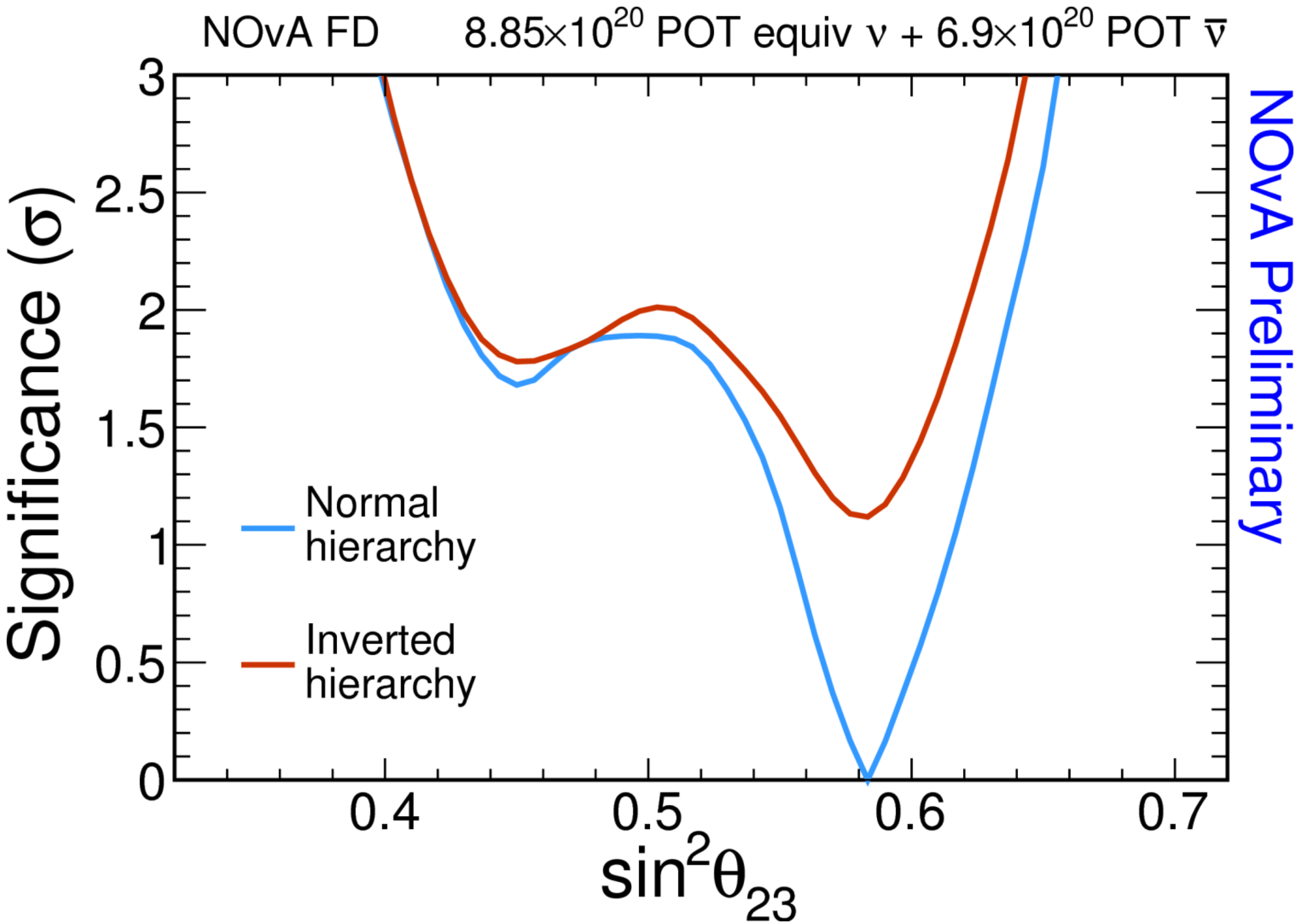


Best Fit

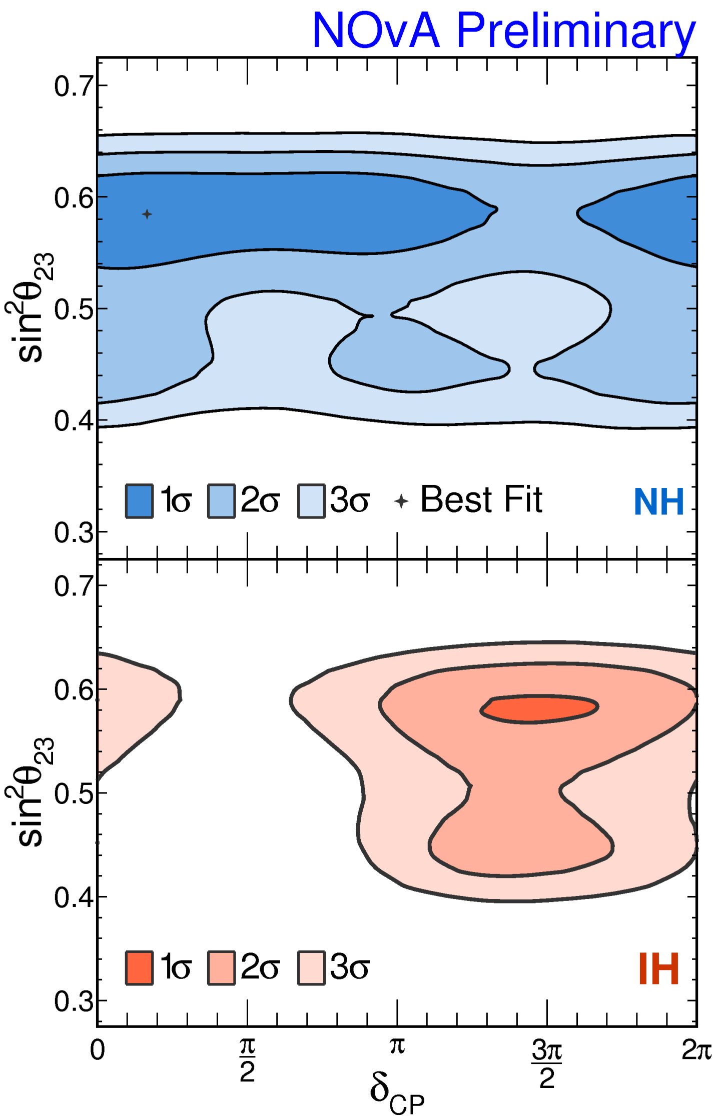
$$\Delta m^2_{32} = 2.51\,^{+0.12}_{-0.08} \times 10^{-3}\ eV^2$$

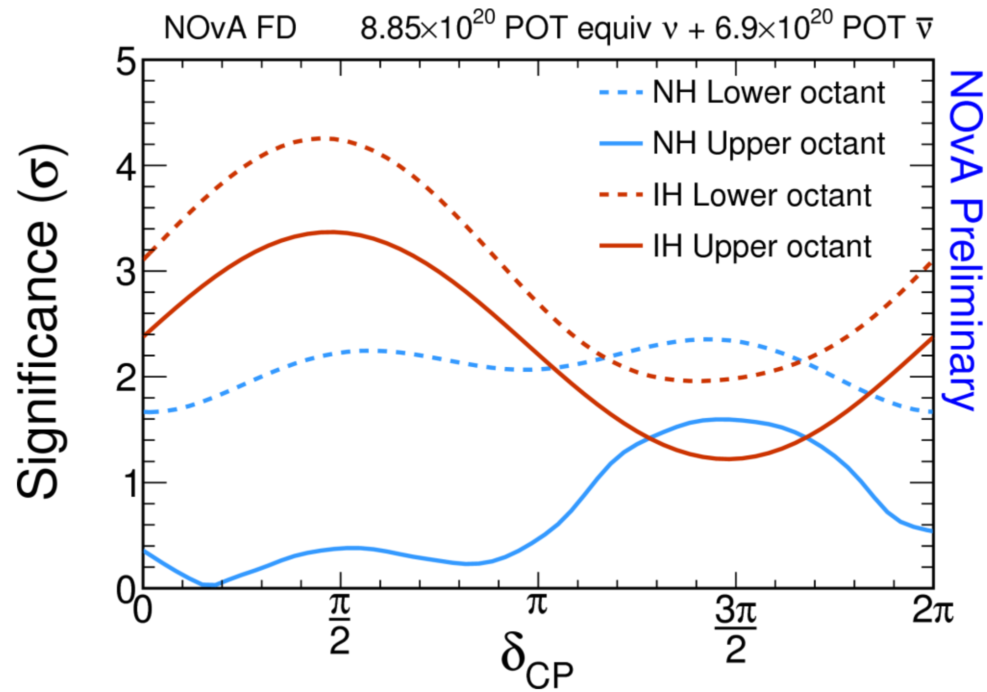
$$\sin^2(\theta_{23}) = 0.58 \pm 0.03$$

Joint Results



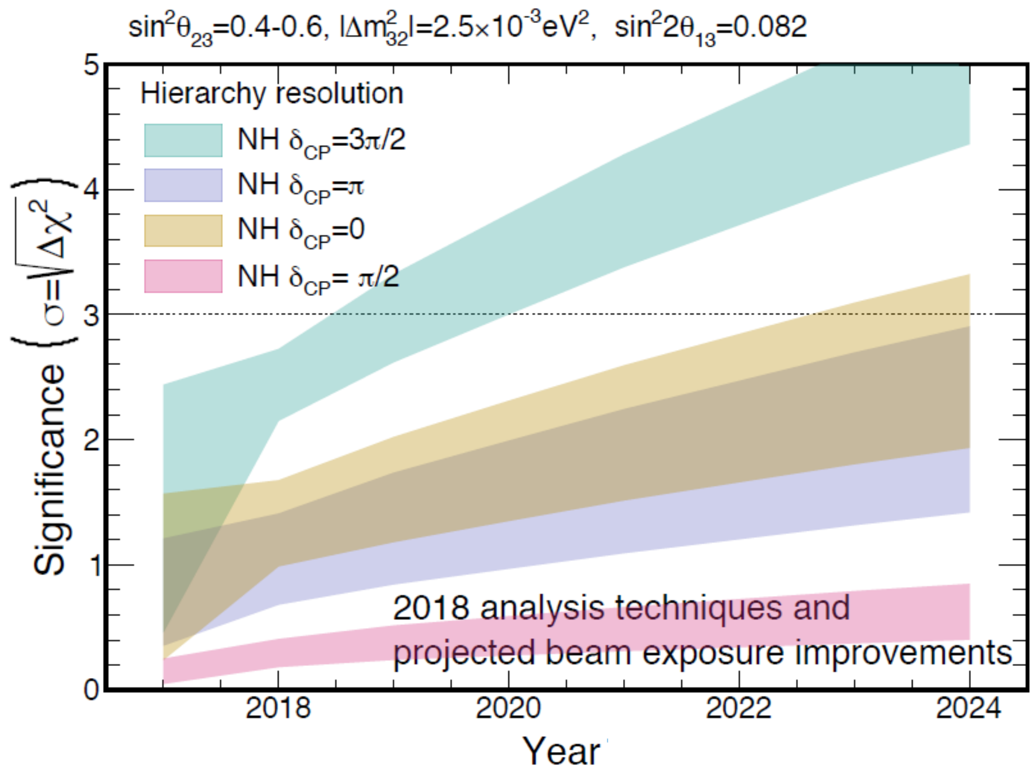
Joint Results





Prefer Normal Hierarchy at 1.8σ

Future



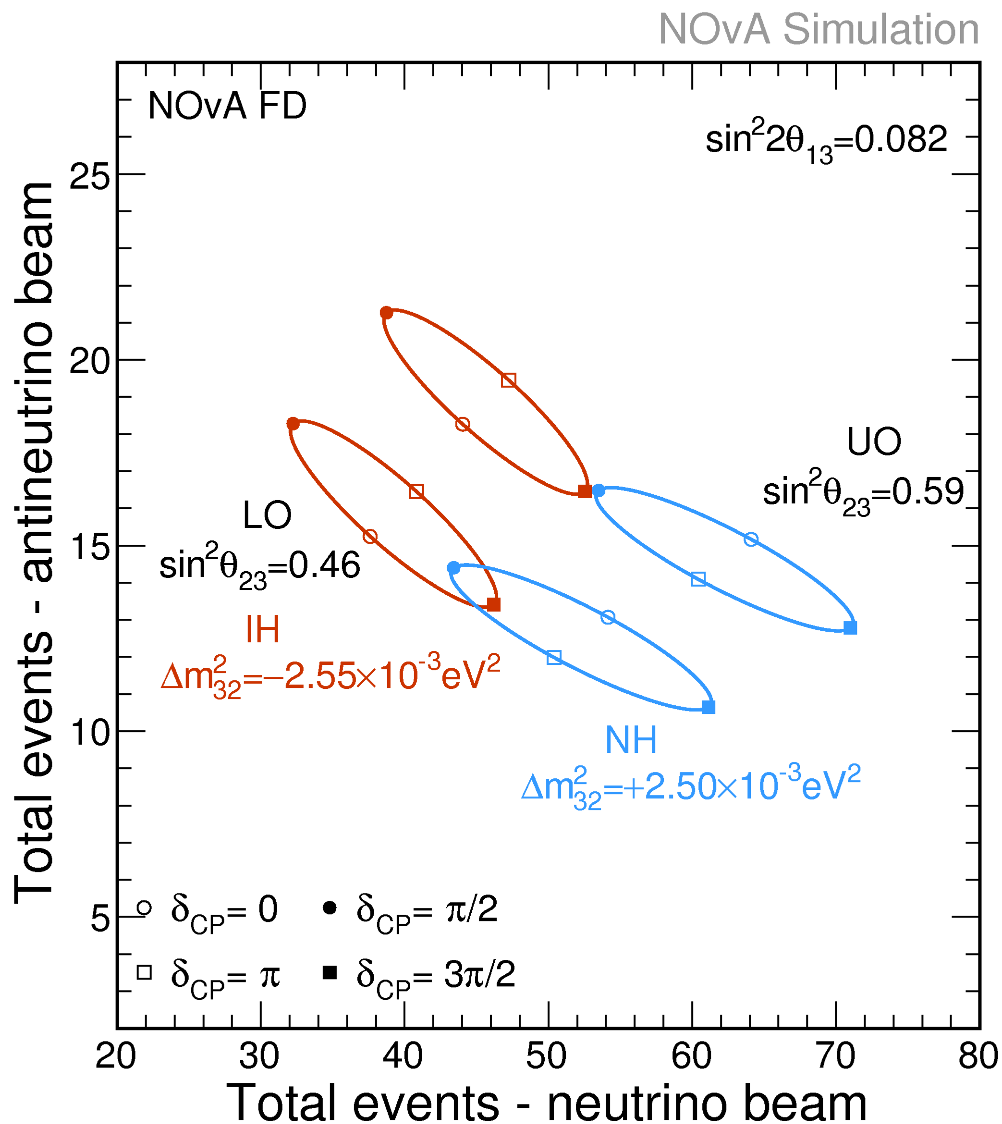
3σ sensitivity to the hierarchy possible in 2020 with favorable parameters

3σ sensitivity for 30-50% of δ_{CP} range by 2024

2σ sensitivity to CP violation in 2024 for favorable parameters

Thank You

Appearance Probability



Appearance Probability