Latest PMNS oscillation results from NOvA

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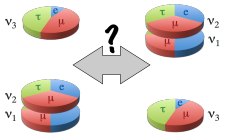
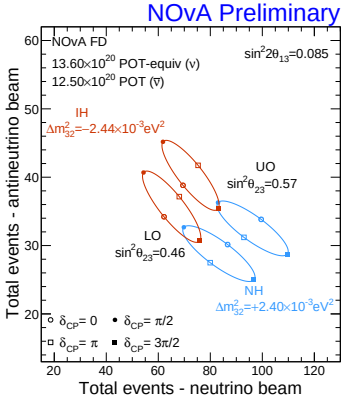
Physics Goals

- Observe:
  $$\nu_\mu \to \nu_\mu \qquad \nu_\mu \to \nu_e$$
  $$\bar{\nu}_\mu \to \bar{\nu}_\mu \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$
- θ_{23} — is it maximal? (ν_3 has equal ν_μ, ν_τ)
- Octant of θ_{23} if not maximal (more ν_μ or ν_τ?)
- Sign of Δm^2_{32} — mass ordering (hierarchy)



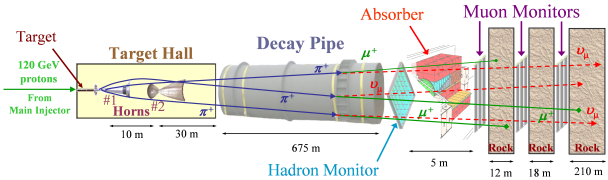
- Discover or constrain CP violation in neutrino sector



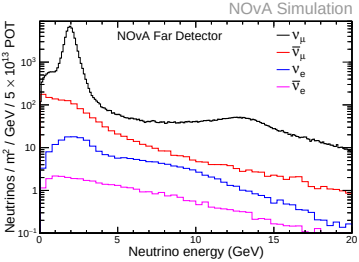
Matter effect enhances (suppresses) ν_e appearance for normal (inverted) ordering

Design Overview

- Fermilab's NuMI beam



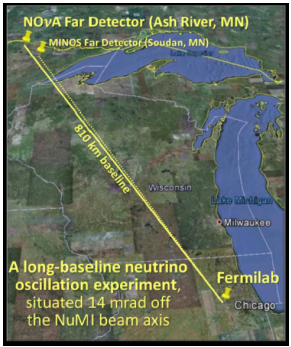
- Off-axis → narrow spectrum at 2 GeV
- 1st oscillation maximum at 810 km



- Near detector
  - Observe unoscillated beam composition, energy
- Far detector observes:

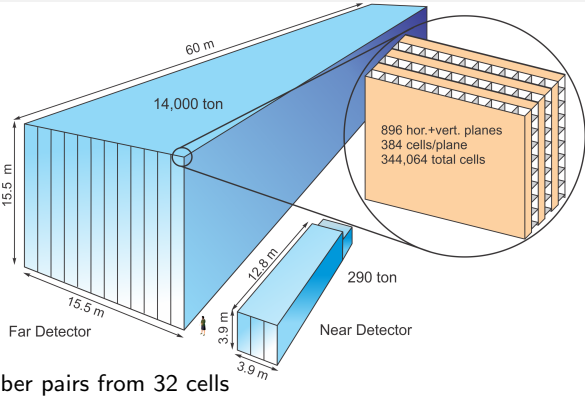
$\nu_\mu \to \nu_\mu \quad \nu_\mu \to \nu_e$

$\bar{\nu}_\mu \to \bar{\nu}_\mu \quad \bar{\nu}_\mu \to \bar{\nu}_e$

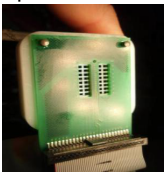


Detector Technology

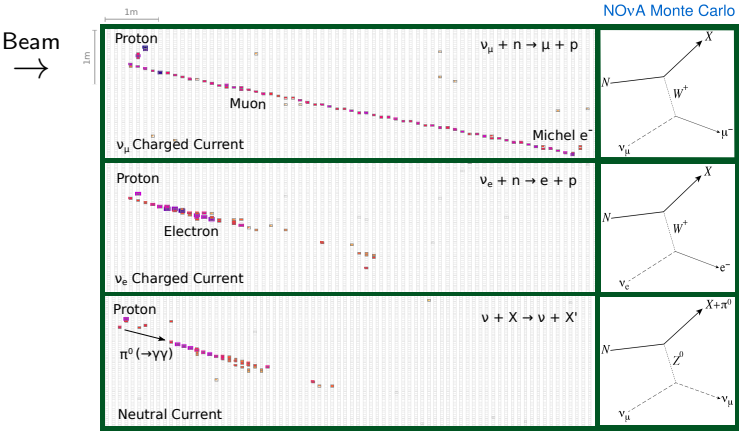
- Two functionally identical detectors
- Segmented plastic and scintillator tracking calorimeter
- 63% active
- APD readout
- Near detector is 300 t, underground, 1 km from NuMI target
- Far detector is 14 kt, on the *surface*



32 pixel APD sees fiber pairs from 32 cells

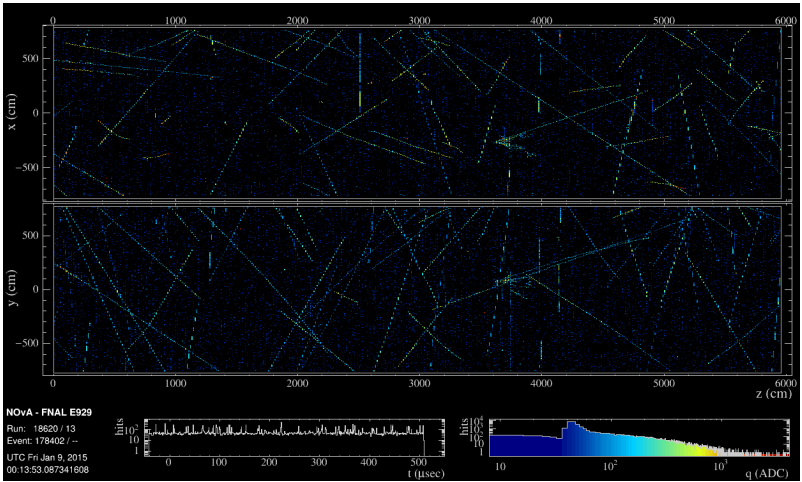


Event Topologies

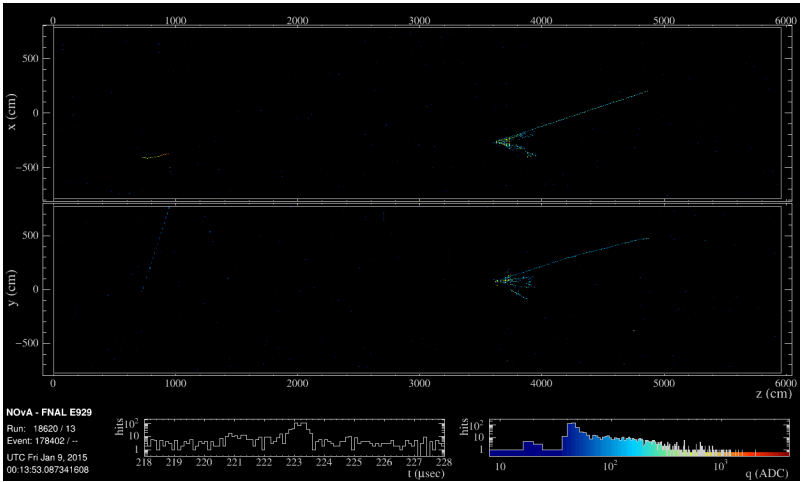


- Optimized for EM showers
- $\sim$6 samples per X_0
- Muon energy measured by range
- All other energy from calorimetry

Cosmic Rejection — 550 μs exposure of the Far Detector — 150 kHz of cosmics



Cosmic Rejection — Zoomed into 10 μs NuMI beam pulse: 10^5 cosmic rejection



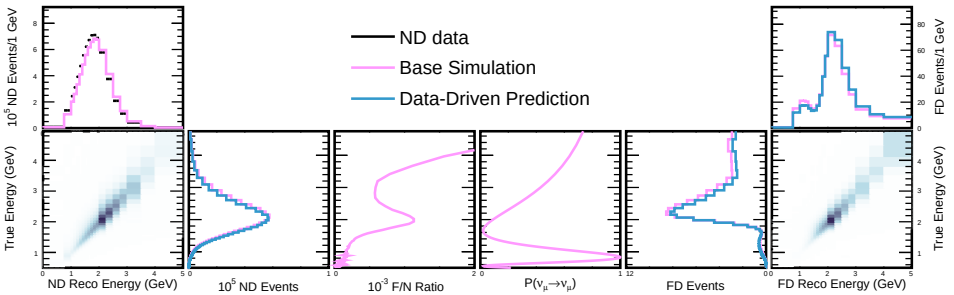
Selection

- Additional factor of 10^7 cosmic rejection needed + must classify neutrino interactions. Single technique for both.
- Novel selection inspired by computer vision techniques: No explicit reconstruction
- Matrices of hit information are fed into a convolutional neural network (CNN)
- Abstract features extracted automatically
- Scores events on hypotheses of ν_e CC, ν_μ CC, NC and cosmic

"A Convolutional Neural Network Neutrino Event Classifier", A. Aurisano et al, **JINST 11 (2016) 09, P09001**, 1604.01444

Predicting the Far Detector Spectrum

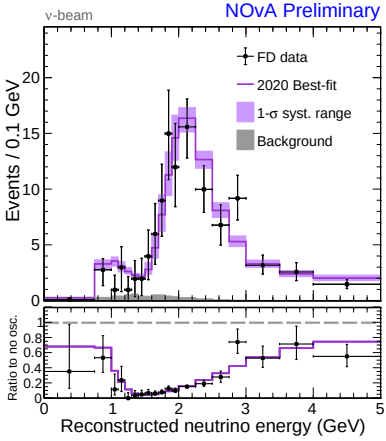
- Near Detector data used to predict Far Detector data given any oscillation parameters



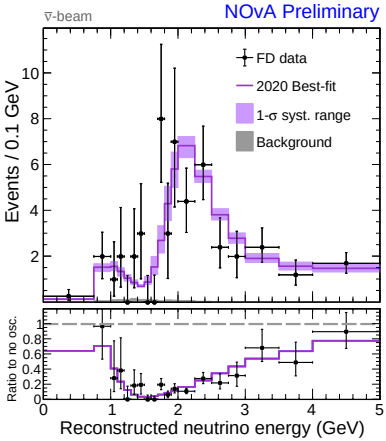
- Uncertainties in flux, cross section and efficiency largely cancel: similar detectors in same beam
- Now extrapolate in bins of p_T: helps account for Near/Far acceptance differences
- But at second order rely on simulation for reco-to-true matrices, Far/Near flux ratio, etc.
  - See "Modelling issues for NOvA" at 17:12 today, WG1+WG2

Far Detector Data: 2013–2020 — ν_μ disappearance

- Neutrino mode: 13.6×10^{20} POT
- 211 events selected
- Background: 9.2 events



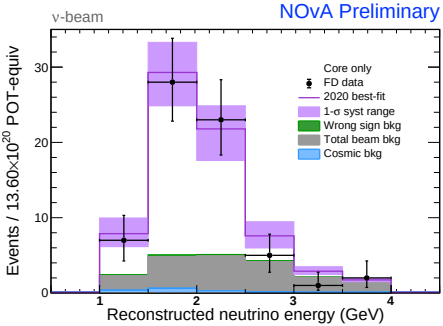
- Anti-neutrino mode: 12.5×10^{20} POT
- 105 events selected
- Background: 2.1 events

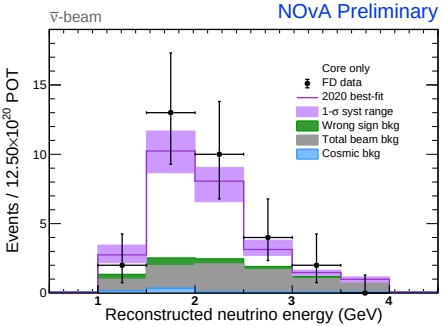


Far Detector Data — ν_e appearance

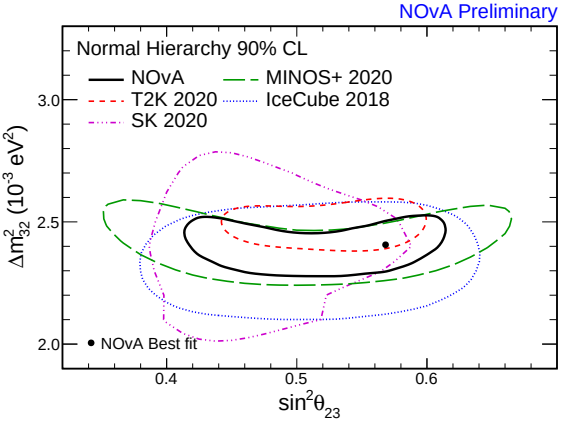
- 82 events in ν mode
- Background: 26.8 events
  - 1.0 wrong-sign (appearing $\bar{\nu}_e$)
  - 22.7 other beam (intrinsic ν_e, ν_μ, ν_τ, neutral current)
  - 3.1 cosmic

- 33 events in $\bar{\nu}$ mode
- Background: 14.0 events
  - 2.3 wrong-sign
  - 10.2 other beam
  - 1.6 cosmic
- $> 4\sigma$ electron anti-neutrino appearance

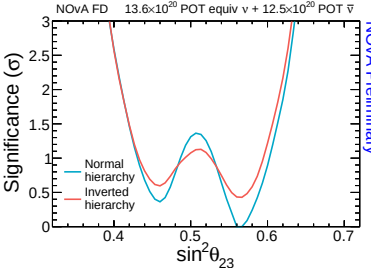




Combined Appearance/Disappearance Results — θ_{23}, Δm^2_{32}

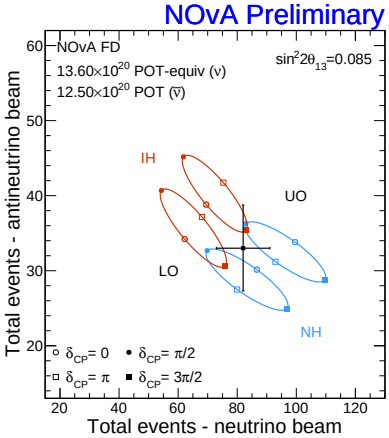


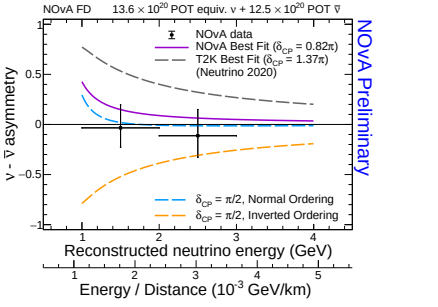
- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\,\mathrm{eV}^2$ (normal hierarchy)



- Slight preference for upper octant, normal hierarchy
- $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$

Combined Appearance/Disappearance Results — Mass ordering, θ_{23}, δ_{CP}

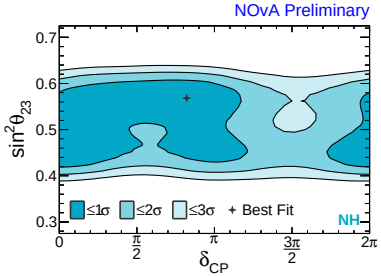




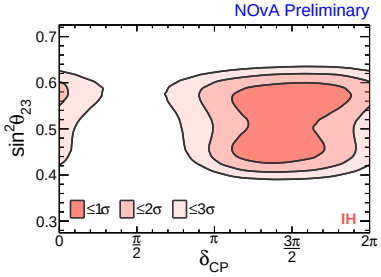
- Combined with ν_μ disappearance data, ν_e appearance favors:
- Normal hierarchy, weakly
- Neither octant significantly
- δ around $\pi/2$ for normal
- δ around $3\pi/2$ for inverted

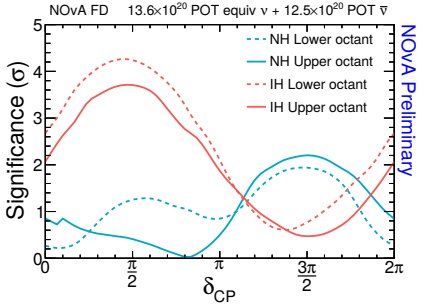
Combined Appearance/Disappearance Results — Mass ordering, θ_{23}, δ_{CP}

Normal hierarchy



Inverted hierarchy



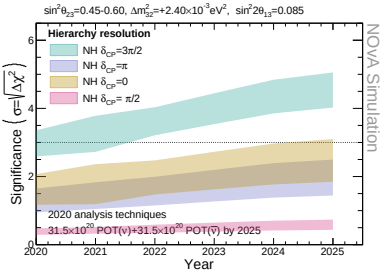


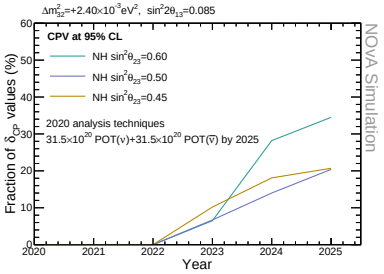
- All values of δ allowed
- Prefer normal hierarchy by 1.0σ
- Prefer **upper octant** by 1.2σ
- Exclude $\delta = \pi/2$ in IH at $> 3\sigma$

Outlook

Sensitivity assuming:

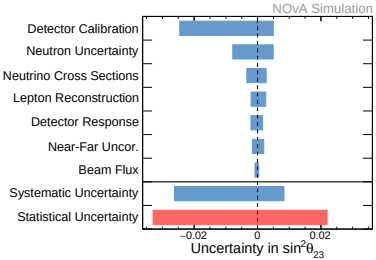
- 50% neutrino mode, 50% antineutrino mode for future running
- 63×10^{20} POT total by 2026 given projected accelerator improvements
- Current analysis techniques (conservative)

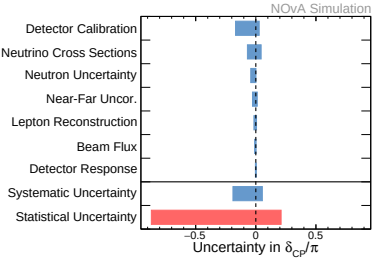


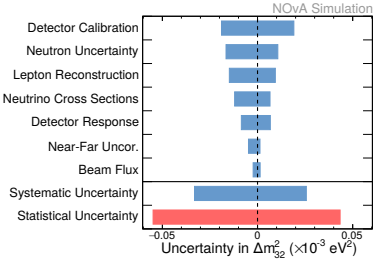


- 3σ hierarchy determination for 30–50% of true δ values (normal hierarchy)
- 95% C.L. CP-violation for 20–35% of true δ values

Systematics







- Statistics dominated
- But systematic uncertainties are important
- Working to reduce all major systematics:
  - Calibration — to be improved by test beam, better modeling
  - Neutron response uncertainty — important for $\bar{\nu}$
  - Neutrino cross sections

Conclusions

- Appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam at $> 4\sigma$
- Excluded $> 3\sigma$: Inverted hierarchy, $\delta \approx \pi/2$
- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\,\mathrm{eV}^2$
- $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$
- 2108.08219

- More NOvA talks coming up
- Jeremy Hewes: sterile neutrino search, WG5 today 17:00
- Greg Pawloski: cross-section modeling, WG1+WG2 today 17:12
- Leonidas Aliaga Soplin: ν_μ cross sections, WG2 tomorrow 16:20
- Bryan Ramson: interactions with EM showers in the final state, WG2 tomorrow 16:40