Measurements of the Atmospheric Neutrino Oscillation Parameters (and others) with NOvA

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July 30, 2019
Design Overview

- Fermilab’s NuMI beam
- Near detector
  - Measures unoscillated beam composition, energy spectrum
- Far detector
  - Observes oscillations from mixing parameters $\theta_{13}, \theta_{23}, \delta_{\text{CP}}, |\Delta m^2_{32}|$, $\text{sgn}(\Delta m^2_{32})$

- Off-axis $\rightarrow$ narrow spectrum at 2 GeV
- 1st oscillation maximum at 810 km
Physics Goals

- Observe:
  \[
  \nu_\mu \rightarrow \nu_\mu \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \\
  \nu_\mu \rightarrow \nu_e \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e
  \]

- \( \theta_{23} \) — is it maximal? (\( \nu_3 \) has equal \( \nu_\mu, \nu_\tau \))

- Octant of \( \theta_{23} \) if not maximal (more \( \nu_\mu \) or \( \nu_\tau \)?)

- Sign of \( \Delta m^2_{32} \) — mass ordering (hierarchy)

- Discover or constrain CP violation in neutrino sector

- Are there additional sterile neutrinos?

- Neutrino cross-sections

- Astrophysics

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**NOvA Simulation**

[Diagram showing neutrino oscillations and matter effects]

- Matter effect enhances (suppresses) \( \nu_e \) appearance for normal (inverted) ordering
Detector Technology

- Two functionally identical detectors
- Segmented plastic and scintillator sampling 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, 810 km north

32 pixel APD sees fiber pairs from 32 cells
Design

Event Topologies

\[ \nu_\mu + n \rightarrow \mu + p \]

\[ \nu_e + n \rightarrow e + p \]

\[ \nu + X \rightarrow \nu + X' \]

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NOvA Monte Carlo

Proton

Muon

\( \nu_\mu \) Charged Current

Michel e^-

Electron

\( \nu_e \) Charged Current

Proton

Neutral Current

\( \pi^0 \rightarrow \gamma \gamma \)
Cosmic Rejection — 550 $\mu s$ exposure of the Far Detector — 150 kHz of cosmics
Cosmic Rejection — Zoomed into 10µs NuMI beam pulse: $10^5$ cosmic rejection
... and zoomed in spatially

- Selection cuts and convolutional neural net classifier reduce background by a further $10^7$
\( \nu \) \(_{\mu} \) Far Detector Data

Data from 2013 to 2019

- Neutrino mode: \( 8.85 \times 10^{20} \) protons-on-target
- 113 events selected
- Background: 4.2 events, half cosmic, half beam

- Anti-neutrino mode: \( 12.33 \times 10^{20} \) protons-on-target
- 102 events selected
- Background: 2.2 events: 0.8 cosmic, 1.4 beam
Selected Events — $\nu_e$

- Selected 58 events in FD in $\nu$ mode
- Background: 14.7 events
  - 11 beam (intrinsic $\nu_e$, $\nu_\mu$, $\nu_\tau$, neutral current)
  - 0.7 wrong-sign (appearing $\bar{\nu}_e$)
  - 3 cosmic

- Selected 27 in $\bar{\nu}$ mode
- Background: 10.3 events
  - 7.0 beam
  - 2.2 wrong-sign
  - 1.1 cosmic

- 4.4$\sigma$ electron anti-neutrino appearance
  - Only world observation of $\nu_e$ appearance
Combined Appearance/Disappearance Results — Mass ordering, $\theta_{23}$, $\delta_{\text{CP}}$

**NOvA Preliminary**

- Total events - neutrino beam
  - $10, 20, 30, 40, 50$
- Total events - antineutrino beam
  - $= 0$

**CP Equation**

- $\delta_{\text{CP}}/2 \pi \approx \delta_{\text{CP}} \pi$ $= \delta_{\text{CP}} \pi/2$

**Mass Differences**

- $\Delta m_{21}^2 = 2.54 \times 10^{-3} \text{eV}^2$
- $\Delta m_{32}^2 = 2.48 \times 10^{-3} \text{eV}^2$

**Flavor Distribution**

- $\nu$ POT-equiv: $20 \times 8.85$
- $\nu$ POT: $20 \times 12.33$

**Significance**

- Prefer normal hierarchy by $1.9\sigma$
- Prefer upper octant by $1.6\sigma$
- Exclude $\delta = \pi/2$ in IH at $>3\sigma$

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NOvA Preliminary

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Combined Appearance/Disappearance Results — $\theta_{23}$, $\Delta m_{32}^2$

\[ \Delta m_{32}^2 = (2.48^{+0.10}_{-0.06}) \times 10^{-3} \text{ eV}^2 \ (\text{NH}) \]

\[ \sin^2 \theta_{23} = 0.56^{+0.04}_{-0.03} \ (\text{upper octant}) \]
Systematics

- **Statistics dominated**
- **But systematic uncertainties are important**
- **Working to reduce all major systematics:**
  - Neutron response uncertainty — important for $\bar{\nu}$
  - Calibration — to be improved by 2019 test beam
  - Neutrino cross sections
Astrophysics with NOvA

- Large fine-grained detectors support a variety of astrophysical analyses
- Far Detector sensitive to slow, intermediate-mass magnetic monopoles

**Galactic core-collapse supernovae**
- 2200 inverse beta decay events at 10 kpc
- Burst of 2–4 hit clusters

- Seasonal dependence of multi-muon cosmics in Near Detector

**Straight through-going, slow tracks**

**Plus multi-messenger astrophysics with gravitational waves, dark matter searches, n̅n oscillation, and more...**
Conclusions

- Observed appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam at $4.4\sigma$
- Favor normal hierarchy at $1.9\sigma$
- Inverted and $\delta$ around $\pi/2$ excluded at $3\sigma$

- Plan to run until 2025
  - Potential $3\sigma$ reach for mass ordering
  - Potential $2\sigma$ sensitivity to CP violation
- Astrophysics! — poster PS3-219 today & tomorrow
  - And posters PS1-131, PS1-103 in session 1
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.

- But at second order rely on simulation for reco-to-true matrices, Far/Near flux ratio, etc.
Backups
Systematics

- Statistics dominated
- But systematic uncertainties are important. Leading:
  - Calibration — to be improved by 2019 test beam program
  - Neutrino cross sections
  - Neutron response uncertainty — important for $\bar{\nu}$
Results — $\nu_\mu$ Only

- Neutrinos and anti-neutrinos are fit together assuming CPT

![Plot showing Normal and Inverted solutions for NOvA](image)
Delta sensitivity

\[
\sin^2 2\theta_{13} = 0.082, \quad \sin^2 2\theta_{23} = 1.00
\]

\[
\nu \times 36 \times 10^{20} + \bar{\nu} \times 36 \times 10^{20}
\]

NOvA Simulation

Inverted Normal

\[
\sigma = 1.00 \quad 23\theta_{23}^2 = 0.082, \quad \sin 13\theta_{23}^2 \sin \theta
\]

\[
POT
\]

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Wrong-sign cross section

![Graph showing the ratio of wrong-sign to wrong-sign cross sections for NOvA data compared to predictions by GENIE v284, MINERvA, GGM 1973, ITEP 1979, and MINOS 2009. The graph plots the ratio of wrong-sign to wrong-sign cross sections against neutrino energy in GeV.]
We enable GENIE’s empirical “meson exchange current” (MEC) model

Accounts for interactions on correlated nucleon pairs leading to multi-nucleon knockout (two particle, two hole: 2p2h)

All remaining $\nu_\mu$ excess in data is used to scale MEC in 2D bins of $(q_0, |q|)$

By construction, tuned MC closely matches the data
Near Detector Data/MC Agreement After Tune

- After tune, data & MC agree up to 1.3% normalization difference for $\nu$ beam (0.5% for $\bar{\nu}$ beam)
- Shapes shown here — normalization difference removed for display
● Shift quasielastic and resonant events within their (correlated) errors and retune 2p2h to produce MEC error band
Updated Classifier for 2018

- Updated with improved tuning
- Optimized separately for neutrino and anti-neutrino beams
- Cosmic data included in training
Selection — $\nu_\mu$

- In selected $\nu_\mu$ CC events, muon is selected using conventional kNN based on muon track length, scattering, fraction of planes with hadronic energy, $dE/dx$
- Events without a sufficiently muon-like track are rejected

[Graphs and plots showing data distribution and comparison between simulated and experimental results.]
Birks, Cherenkov changes

NOvA Simulation

Light Models: Normalized to Minimum Ionization

- 2016 Birks-Chou Model
- 2017 Birks Model + Cherenkov Light

Proton KE ≈ 390 MeV
\(v_e\) Appearance

- Depends simultaneously on \(\theta_{13}, \theta_{23}, \delta_{\text{CP}}, \text{sign}(\Delta m^2_{31})\)
- \(\sin^2 2\theta_{13} = 0.095 \Rightarrow \text{most } \nu_\mu \text{ go to } \nu_\tau\)
- Look for deviations due to hierarchy (matter effects) and CP-violation

- NOvA measures \(P(\nu_\mu \to v_e)\) and \(P(\bar{\nu}_\mu \to \bar{v}_e)\) at 2GeV, different dependence on \(\text{sign}(\Delta m^2_{32})\) and \(\delta_{\text{CP}}\)
$\nu_e$ Appearance

- $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{32}^2$
- $\alpha \sin 2\theta_{13} \cos \delta \frac{\sin(aL)}{aL} \sin(\Delta_{31} - aL) \cos \Delta_{32} - \alpha \sin 2\theta_{13} \sin \delta \frac{\sin(aL)}{aL} \sin(\Delta_{31} - aL) \sin \Delta_{32}$
- $\sin^2 2\theta_{13} = 0.095 \rightarrow$ most $\nu_\mu$ go to $\nu_\tau$
- Look for deviations due to hierarchy (matter effects) and CP-violation

- NOvA measures $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at 2GeV, different dependence on $\text{sign}(\Delta m_{32}^2)$ and $\delta_{CP}$
- $P \propto \sin^2 \theta_{23}$
- Constrain a space region
Outlook

Sensitivity assuming:

- 50% neutrino mode, 50% antineutrino mode; anti-neutrino for rest of 2018
- $36 \times 10^{20}$ POT of each by 2024 given projected accelerator improvements
- Current analysis techniques (conservative), but modestly improved systematics

- For normal hierarchy, $3\sigma$ for $>30\%$ of true $\delta$ values by 2024
- $3\sigma$ rejection of maximal mixing if true $\sin^2 \theta_{23} < 0.43$ or $> 0.59$