Extraction of Neutrino Oscillation Parameters using Neutrino and Anti-neutrino Data with the NOvA Experiment

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Outline

• Basic, important and unanswered questions in the neutrino sector

• Introduction to the NOvA experiment and detectors

• Production of neutrino beam at Fermilab

• $\nu_\mu$ disappearance and $\nu_e$ appearance data and predictions

• Results of the simultaneous fit to the disappearance and appearance data

• Summary
Unanswered Questions in the Neutrino Sector

- **Mass hierarchy:** Do neutrino masses follow normal or inverted mass hierarchy?

- **CP violation ($\delta_{CP}$):** Are neutrinos different from anti-neutrinos?

- **$\theta_{23}$ angle:** Does $\nu_\mu$ and $\nu_\tau$ mixes maximally?
The NOvA Experiment

- **NOvA (NuMI Off-Axis $\nu_e$ Appearance)** is a two detector, long-baseline, neutrino oscillation experiment
  - **NuMI (Neutrinos at Main Injector)** is 95% $\nu_\mu$ in neutrino mode and 93% $\bar{\nu}_\mu$ in anti-neutrino mode
  - NOvA is 14.6 mrad off-axis from the NuMI beam, observed energy spectrum peaks at 2 GeV peak
  - The Near detector (ND) is onsite at Fermilab, 1 km from neutrino source
  - The Far detector (FD) at Ash River, MN, 810 km from the target

- **Oscillation channels:**
  - $\nu_\mu \rightarrow \nu_\mu$ disappearance
  - $\nu_\mu \rightarrow \nu_e$ appearance
  - Anti-neutrino modes
NOvA Detectors

• NOvA far and near detectors are functionally identical

  » Liquid scintillator detectors and made up of polyvinyl chloride (PVC)
  » Alternating horizontal and vertical planes are used to make 3D tracks of the charged particles

• The neutrino beam is measured by the ND before oscillations and by the FD after oscillations

• The functionally identical ND is also used to make predictions of signal and background components in the FD
• A beam of high energy protons from the Main Injector impinge on a fixed graphite target producing pions and kaons
• Magnetic horns select particles of the desired charge & momentum and focus them into a narrow beam
• Charged pions and kaons decay into muons and neutrinos in the decay pipe
• Rock after absorber filters out muon neutrinos
• Finally we are left with a beam of muon neutrinos
Event Topologies in NOvA

- $\nu_\mu$ CC is the signal for the $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance analysis
- $\nu_e$ CC is the signal for the $\nu_e$ ($\bar{\nu}_e$) appearance analysis
- NC is the background in above analyses
Extrapolation - FD Signal Prediction

- To make signal prediction in the FD, we start by measuring the neutrino spectrum in the ND and convert it to true energy distribution.
- The measured spectrum in the ND is combined with the ratio of Far over Near (F/N) simulations and the oscillation probabilities for disappearance or appearance signal.
- The extrapolated distribution in the true energy is converted to the reconstructed energy by using $E_{\text{True}} \rightarrow E_{\text{Reco}}$ 2D energy matrix resulting into signal prediction in the FD.

![Graphs showing ND and FD data comparison](image-url)
Extrapolation - Systematic Uncertainty

- Same extrapolation technique is used to extrapolate systematic uncertainty from the ND to the FD
- The ND data is replaced by the ND simulation under a systematic shift
- The systematically shifted simulation in the ND is then lead to the systematically shifted prediction in the FD
- Many of the systematic uncertainties cancels in the F/N ratios
Systematics in NOvA Analyses

- Systematic uncertainties are included as nuisance parameters in the fit for all analyses

The detector calibration and cross-section are two of the biggest systematics but we are still dominated by the statistical uncertainties.
• Observe 113 events in the neutrino mode (expected 730 w/o oscillation) and 65 in the antineutrino mode (expected 266 w/o oscillation)
• Clear evidence of the oscillations
**ν_μ** Fit to the Disappearance Data

- Disappearance data is fitted for the Δm^2_{32} and sin^2θ_{23} parameters
- At 90% C.L. the muon neutrino and anti-neutrino datasets prefer upper octant (UO; sin^2θ_{23} > 0.5) for the normal hierarchy (NH) and lower octant (LO; sin^2θ_{23} < 0.5) for the inverted hierarchy (IH)
• Observe 58 events in the neutrino mode (expected 15 background events) and 18 in the anti-neutrino mode (expected 5.3 background events)

• Electron anti-neutrino appearance of $> 4\sigma$
Simultaneous Fit of the Disappearance and Appearance Data

- Appearance Data is fitted for the $\sin^2\theta_{23}$ and $\delta_{\text{cp}}$ parameters
- Best Fit parameters
  - $\delta_{\text{cp}} = 0.17\pi$
  - $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
  - $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3}$ eV$^2$
- Prefer NH at 1.8σ
- Exclude $\delta_{\text{cp}} = \pi/2$ in the IH at >3σ
Summary

• NOvA is a two detector, long-baseline, accelerator based neutrino oscillation experiment

• The Near Detector measures NuMI beam before oscillations and helps in signal and background predictions in the Far Detector

• Having two functionally identical detectors is advantageous for cancelling uncertainties that are common between the two detectors

• Best fit to the $\nu_\mu$ disappearance data prefer UO for the NH and LO for IH

• A simultaneous fit of the disappearance and appearance data prefer NH at 1.8\( \sigma \) and exclude $\delta_{CP} = \pi/2$ in the IH at >3\( \sigma \)
Backup
• The NuMI beam is 95% has $\nu_\mu$ component in the neutrino beam mode and 93% $\bar{\nu}_\mu$ in the antineutrino beam mode
Off-axis configuration

- At 14.6 mrad off axis the neutrino spectrum becomes narrow, monochromatic around 2 GeV energy
- $\nu_\mu \rightarrow \nu_e$ appearance probability maximizes near 2 GeV neutrino energy

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$E_\nu = \frac{0.43E_\pi}{1 + \gamma^2\theta^2}.$$
$\nu_\mu \rightarrow \nu_e$ Appearance Oscillation Probability

\[
P(\nu_\mu \rightarrow \bar{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}
\]

\[
\Delta = \frac{\Delta m^2_{31} L}{4E}
\]

\[
A = \frac{G_F n_e L}{\sqrt{2} \Delta}
\]
PMNS Matrix

$$U = \begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{bmatrix} \begin{bmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{bmatrix} \begin{bmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
e^{i\alpha_1/2} & 0 & 0 \\
0 & e^{i\alpha_2/2} & 0 \\
0 & 0 & 1
\end{bmatrix}$$

$$P(\nu_\mu \rightarrow \nu_\tau) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$+ 2\alpha \sin \theta_{13} \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin \Delta$$

$$+ 2\alpha \sin \theta_{13} \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos \Delta$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \quad \Delta = \Delta m^2_{31} L/(4E) \quad A = \frac{\nu_e}{\nu_\mu} L/(\sqrt{2}\Delta)$$
Cosmic Events

NOvA 2018 Results
Neutrino Event

NOvA 2018 Results
The detector calibration and cross-section are two of the biggest systematics but we are still dominated by the statistical uncertainties.
Neutrino and anti neutrino data are divided into different quartiles based on the hadronic energy fraction in the total reconstructed neutrino energy.
The contours for the $\nu_\mu$ and $\bar{\nu}_\mu$ data are shown.
\( \chi^2_i = 2 \times \left( F_i^{Predicted} - F_i^{Data} + F_i^{Data} \ln \frac{F_i^{Data}}{F_i^{Predicted}} \right) \)
• 8.85e20 neutrino POT from February 2014 to February 2017
• 6.9e20 anti-neutrino POT from February 2017 to April 2018
Neutrino Interactions

![Graph showing neutrino interactions with energy versus cross-section ratio.](image)