New Perspectives 2022

NOvA in 10 minutes
(or your neutrino is free!)

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Neutrino Oscillations

- In the 20th century many experiments studying neutrinos saw discrepancies in neutrino rates.

- Eventually it was proposed that neutrino oscillations were to blame for these discrepancies.

- Oscillations are governed by the PMNS matrix.

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\
0 & -\sin(\theta_{23}) & \cos(\theta_{23})
\end{pmatrix}
\begin{pmatrix}
\cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\
0 & 1 & 0 \\
-\sin(\theta_{13})e^{i\delta} & 0 & \cos(\theta_{13})
\end{pmatrix}
\begin{pmatrix}
\cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\
-sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\
n0 & 0 & 1
\end{pmatrix}
\]

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i U_{\beta i}^* U_{\alpha i} e^{-i\frac{m_i^2 L}{2E}} \right|^2
\]
NOvA: Physics Goals

1. **CP**: Are neutrinos CP violating particles?  
   What is the value of $\delta_{CP}$?

2. **Mass Hierarchy**: Is $m_3$ heavier or lighter than $m_{2/1}$?

3. **Mixing**: Is $\theta_{23}$ exactly 45°? If not, is it above or below 45°?

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix} \begin{pmatrix} \cos(\theta_{13}) & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta} & 0 & \cos(\theta_{13}) \end{pmatrix} \begin{pmatrix} \cos(\theta_{12}) & \sin(\theta_{12}) & 0 \\ -\sin(\theta_{12}) & \cos(\theta_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

**Side quests:**
- Cross section measurements
- Cosmic Ray physics
- Supernova neutrino detection
- Sterile Neutrino searches
- Magnetic monopole searches
- and more!
Oscillation Probabilities in vacuum

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - [\sin^2(2\theta_{13})\sin^2(\theta_{23}) + \cos^4(\theta_{13})\sin^2(2\theta_{23})] \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right) \]

\[ P(\nu_\mu \rightarrow \nu_e) = P_{atm} + 2\sqrt{P_{atm}\sqrt{P_{sol}}} \left(\cos\Delta m_{32}^2 \cos\delta \mp \sin\Delta m_{32}^2 \sin\delta\right) + P_{sol} \]

- CP dependence

\[ \sqrt{P_{atm}} = \sin\theta_{23} \sin2\theta_{13} \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \]

\[ \sqrt{P_{sol}} = \cos\theta_{23} \sin2\theta_{12} \left(\frac{\Delta m_{21}^2 L}{4E}\right) \]

- \( m_{atm}^2 = \Delta m_{31}^2 = m_3^2 - m_1^2 = 2.5 \times 10^{-3} \text{ eV}^2 \)

- \( m_{sol}^2 = \Delta m_{21}^2 = m_2^2 - m_1^2 = 7.6 \times 10^{-5} \text{ eV}^2 \)
Untangling $\delta$

\[\delta_{cp} = 0\]

\[\delta_{cp} = \frac{\pi}{2}\]

\[\delta_{cp} = 0 \rightarrow 2\pi\]

In Vacuum
Untangling Mass Hierarchy

NOvA: L=810 km, E=2.0 GeV

Vacuum Oscillations

Oscillations including Matter Effects
Untangling $\theta_{23}$

Maximal Mixing
$\theta_{23}=45^\circ$

Upper vs Lower Octant
$\theta_{23}>45^\circ$, $\theta_{23}<45^\circ$
Neutrinos at the Main Injector (NuMI)

- Focusing horns allow for neutrino and antineutrino configuration
- NOvA is 14.6 mrad off-axis to minimize backgrounds
- Neutrino energies peak at ~2 GeV
- NuMI new power record: 893 kW

![NOvA Simulation](image)
The NuMi Off-axis $\nu_e$ Appearance Experiment

- Predominantly muon (anti)neutrino beam
- 14.6 mrad off-axis
- Two functionally equivalent liquid scintillator detectors
  - Far Detector 14 kt
  - Near Detector 300 t
- Detectors are separated by 809 km

- Physics goals:
  - Mass Ordering, CP phase, $\theta_{23}$
Detector Overview

To 1 APD pixel

View from the top

Interaction Point

Particle 1

Particle 2

Particle 3

Neutrino from Fermilab

PVC cell filled with liquid scintillator

View from the side

Interaction Point

Particle 2

Particle 1

Particle 3

Neutrino from Fermilab

1 meter
NOvA 2020 Results

Best Fit:

Normal hierarchy
\[ \Delta m^2_{23} = (2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2 \]

Upper Octant
\[ \sin^2 \theta_{23} = 0.57^{+0.04}_{-0.03} \]
\[ \delta = 0.82 \pi \]
Statistics are currently the largest uncertainty in our measurements
Summary

- NOvA is a long baseline neutrino oscillation experiment trying to better understand Mass Ordering, CP phase, and $\theta_{23}$.

- Joint fit with T2K coming later this year!

We are taking some time to work on our side quests and increase the size of our oscillation dataset to come back better than ever!
Thank you!
Gracias!
Backup slides
Oscillations in Matter

$\nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) = P_{\text{atm}} + 2\sqrt{P_{\text{atm}}}\sqrt{P_{\text{sol}}} \left(\cos\Delta_{32} \cos\delta \mp \sin\Delta_{32} \sin\delta\right) + P_{\text{sol}}$$

$$\sqrt{P_{\text{atm}}} = \sin\theta_{23} \sin2\theta_{13} \frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL} \left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$\sqrt{P_{\text{sol}}} = \cos\theta_{23} \sin2\theta_{12} \frac{\sin(aL)}{aL} \left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$\Delta_{jk} \equiv \frac{\Delta m_{jk}^2 L}{4E}$$

$$a = \frac{G_F N_e}{\sqrt{2}}$$

$$\Delta m_{jk}^2 = m_j^2 - m_k^2$$
NOvA Reconstruction Chain

1. **Slicing**
   (coarse event-level time-space clustering)

2. **2D Guideline Finding**
   (2-point Hough transform)

3. **Vertex Reconstruction**
   (Elastic arms)

4. **2D Prong Formation**
   (fuzzy k-means)

5. **3D Prong Matching**

6. **νe CC Event ID**
   (neural network)
Event classification

\( \nu_\mu CC \)

\( \nu_e CC \)

\( NC \)
NOvA Energy Reconstruction for CC

\( \nu_e \) interaction

\( E_{\text{HAD}} \)

\( E_{\text{EM}} \)

\( E_{\text{EM}} \) and \( E_{\text{HAD}} \) from calorimetry

\( \nu_\mu \) interaction

\( E_{\text{HAD}} \)

\( E_\mu \) calculated from track length

\( E_\mu \)
Looking at $\nu_\mu$ CC

$\nu_\mu$ interaction

$E_\text{HAD}$

$E_\mu$

NOvA in 10 minutes | Maria Manrique Plata
Projected Sensitivities

NOvA Simulation

Signif. of Discovering CP Violation (σ)

- NO, δ_{CP} = π/2
- NO, δ_{CP} = 3π/2

POT (×10^{20})

Year

2021 2022 2023 2024 2025 2026

Signif. of Resolving Mass Ordering (σ)

- NO, δ_{CP} = 0
- NO, δ_{CP} = π/2
- NO, δ_{CP} = π
- NO, δ_{CP} = 3π/2

POT (×10^{20})

Year

2021 2022 2023 2024 2025 2026
NOvA vs T2K

T2K, NEUTRINO 2020:  
- BF  
- ≤ 90% CL  
- ≤ 68% CL

NOvA:  
- BF  
- ≤ 90% CL  
- ≤ 68% CL

Normal Ordering

Inverted Ordering
NOvA Exposure
NOvA with friends

Normal Ordering 90% CL

- NOvA
- MINOS+ 2020
- T2K Nature 580
- IceCube 2018
- SK 2018

Best fit

$\Delta m_{32}^2 \ (10^{-3} \text{ eV}^2)$ vs $\sin^2 \theta_{23}$