Results from NOvA and T2K

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Neutrino Oscillations
Big Picture Neutrino Oscillation Questions

- Is there significant CP violation in the neutrino sector?
- What is the mass ordering of the neutrino mass states?
- What are the precise values of the remaining neutrino oscillation parameters?
- Could neutrino sector CP violation explain the matter/anti-matter asymmetry?
Is there significant CP violation in the neutrino sector?

What is the mass ordering of the neutrino mass states?

Could neutrino sector CP violation explain the matter/anti-matter asymmetry?

What are the precise values of the remaining neutrino oscillation parameters?
Neutrino Oscillation: PMNS

Interaction with matter in flavor eigenstate defined by charged lepton.

\[ \nu_\ell \rightarrow \ell^- \quad \nu_\ell \rightarrow \ell^- \]

Pontecorvo–Maki–Nakagawa–Sakata
Neutrino Oscillation: PMNS

Interaction with matter in flavor eigenstate defined by charged lepton.

Pontecorvo–Maki–Nakagawa–Sakata

Which mass ordering?
Neutrino Oscillation: PMNS

e.g. created as muon neutrinos

Interaction with matter in flavor eigenstate defined by charged lepton.

Propagate as superposition of mass/energy eigenstates.

Pontecorvo–Maki–Nakagawa–Sakata
Neutrino Oscillation: PMNS

Interaction with matter in flavor eigenstate defined by charged lepton.

Interaction with matter in flavor eigenstate defined by charged lepton.

$\nu_\ell \rightarrow W^\pm \rightarrow \ell^- N \rightarrow N'$

Pontecorvo–Maki–Nakagawa–Sakata

Propagate as superposition of mass/energy eigenstates.

Projecting back to flavor eigenstates reveals a different flavor mixture. (if $|\Delta m^2_{ij}| \neq 0$)

$L = 295 \text{ km}$
Re-parameterizing the PMNS

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta_{CP}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

- Unitarity lets us re-parameterize PMNS matrix in terms of:
  - Three mixing angles: \( C_{ij} = \cos(\theta_{ij}) \)
  - CP violating phase: \( 0 < \delta_{CP} < 2\pi \) or \( -\pi < \delta_{CP} < \pi \)
The Experiments
The NOvA Experiment

Photo Credit: Fermilab
The NOvA Experiment
The NOvA Neutrino Flux

NOvA Far Detector

Fiducial Mass: 14 kT
Material: Liquid scintillator
Detection technique: Scintillation
Baseline: 810 km
Peak neutrino energy: 1.9 GeV
Location: Ash River, MN

Expected Unoscillated NOvA $\nu_\mu$ Far Flux

$\Phi$ (Arbitrary Units)

$E_\nu$ (GeV)
The T2K Collaboration

J-PARC, 2014
Tokai To Kamioka

SK Public Gallery

Super-Kamiokande

J-PARC

Mt. Noguchi-Goro
2,924 m

Mt. Ikeno-Yama
1,360 m

Kamioka

1,700 m below sea level

295 km

Neutrino Beam

Near Detectors

Beam center

~10 m

~10 m
Tokai To Kamioka

SK Public Gallery

Super-Kamiokande

Mt. Noguchi-Goro
2,924 m

Mt. Ikeno-Yama
1,360 m

1,700 m below sea level

295 km

Kamioka

Neutrino Beam

Tokai

J-PARC

Near Detectors
The TSK Neutrino Flux

Super Kamiokande

Fiducial mass: \(~22.5\) kT
Material: Ultrapure Water
Detection technique: Cherenkov
Baseline: 295 km
Peak neutrino energy: 0.6 GeV
Location: Mozumi Mine, Gifu, Japan

Expected Unoscillated T2K $\nu_\mu$ Far Flux

$\Phi$ (Arbitrary Units)

$E_\nu$ (GeV)
T2K and NOvA Fluxes

- SK $\nu_\mu$ v-mode Flux
- NOvA $\nu_\mu$ v-mode Flux

![Graph showing FLuxes vs E_v (GeV)]

- $\phi$ (Arbitrary Units)
- $E_\nu$ (GeV)
Measuring Oscillations
Long baseline experiments study two oscillation channels:

- **Muon neutrino disappearance**
  \[ \nu_\mu \rightarrow \nu_\mu \]

- **Electron neutrino appearance**
  \[ \nu_\mu \rightarrow \nu_e \]
Measuring Oscillations

- Long baseline experiments study two oscillation channels:
  - Muon neutrino disappearance
    - $\nu_\mu \rightarrow \nu_\mu$
  - Electron neutrino appearance
    - $\nu_\mu \rightarrow \nu_e$
Muon Neutrino Disappearance Probability

- To leading order, muon neutrino survival probability depends on mixing angles, and mass-squared splittings.

\[
P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2 \theta_{13} \sin^2 \theta_{23} \\
\times [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \frac{\Delta m^2_{32} L}{4E} \\
+ \text{(solar, matter effect terms)}
\]
To leading order, muon neutrino survival probability depends on mixing angles, and mass-squared splittings.

Choose L/E for maximum effect:

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

\[ + \text{(solar, matter effect terms)} \]

\[ \Delta m_{32}^2 = 2.56 \times 10^{-3} \text{ eV}^2 \]

L = 295 km

First maximum
Observing Disappearance

\[ N = \text{Flux} \times \text{Oscillation probability} \]

- \[ \Delta m_{12}^2 = 7.37 \times 10^{-5} \text{ eV} \]
- \[ \Delta m_{32}^2 = 2.46 \times 10^{-3} \text{ eV} \]
- \[ \sin^2(\theta_{12}) = 0.297 \]
- \[ \sin^2(\theta_{13}) = 0.0214 \]
- \[ \sin^2(\theta_{23}) = 0.526 \]
- \[ L = 295 \text{ km} \]
- \[ \delta_{CP} = 0 \]
Observing Disappearance

\[ \text{Number of events } = \text{Flux} \times \text{Oscillation probability} \times \text{Cross section} \]

NEUT 5.3.6, $\nu_\mu^{16}O$

- CC Incl
- CC 0\pi
- CC 1\pi
- CC 2+\pi

$\Delta m^2_{12} = 7.37 \times 10^{-5} \text{ eV}^2$
$\Delta m^2_{32} = 2.46 \times 10^{-3} \text{ eV}^2$

$\sin^2(\theta_{12}) = 0.297$
$\sin^2(\theta_{13}) = 0.0214$
$\sin^2(\theta_{23}) = 0.526$
$\delta_{CP} = 0$

$L = 295 \text{ km}$

$\sigma(E_\nu) \times 10^{39} \text{ cm}^2 / \text{GeV} / \text{A}$

$E_\nu \text{ (GeV)}$

T2K
Observing Disappearance

Flux • Oscillation probability • Cross section

Number of events

NEUT 5.3.6, $\nu_\mu^16O$

--- CC Incl --- CC 0π --- CC 1π --- CC 2+π

$\Delta m^2_{12} = 7.37 \times 10^{-5}$ eV
$\Delta m^2_{32} = 2.46 \times 10^{-3}$ eV
$\sin^2(\theta_{12}) = 0.297$
$\sin^2(\theta_{13}) = 0.0214$
$\sin^2(\theta_{23}) = 0.526$
$\delta_{CP} = 0$

$L = 295$ km

$\sigma(E_v) \times 10^{-39}$ cm$^2$/A vs $E_v$ (GeV)

$\Delta m^2_{12} = 7.37 \times 10^{-5}$ eV
$\Delta m^2_{32} = 2.46 \times 10^{-3}$ eV
$\sin^2(\theta_{12}) = 0.297$
$\sin^2(\theta_{13}) = 0.0214$
$\sin^2(\theta_{23}) = 0.526$
$\delta_{CP} = 0$

$L = 295$ km

Events (Arbitrary Units)

Number of events = Flux • Oscillation probability • Cross section
Disappearance on T2K and NOvA

Number of neutrinos = Flux \cdot Oscillation probability

\[\Delta m^2_{12} = 7.37 \times 10^{-5} \text{ eV} \quad \sin^2(\theta_{12}) = 0.297 \quad L = 295 \text{ km}\]
\[\Delta m^2_{32} = 2.46 \times 10^{-3} \text{ eV} \quad \sin^2(\theta_{13}) = 0.0214 \quad \sin^2(\theta_{23}) = 0.526 \quad \delta_{CP} = 0\]

\[\Delta m^2_{12} = 7.37 \times 10^{-5} \text{ eV} \quad \sin^2(\theta_{12}) = 0.297 \quad L = 810 \text{ km}\]
\[\Delta m^2_{32} = 2.46 \times 10^{-3} \text{ eV} \quad \sin^2(\theta_{13}) = 0.0214 \quad \sin^2(\theta_{23}) = 0.526 \quad \delta_{CP} = 0\]
Measuring Disappearance

\[ |\Delta m_{23}^2| \times 10^{-3} \text{ eV} \]

68% Confidence Level

90%

\( \sin^2(\theta_{23}) \)

\( \Delta \chi^2 \)

Phys. Rev. Lett. 121, 171802
Measuring Disappearance

- Mass-squared splitting shifts the ‘dip’

\( \Delta \chi^2 \)

- 68% Confidence Level
- 90%

\( \Delta m^2_{32} = 2.46 \times 10^{-3} \text{ eV} \)
\( \Delta m^2_{32} = 2.52 \times 10^{-3} \text{ eV} \)
\( \Delta m^2_{32} = 2.32 \times 10^{-3} \text{ eV} \)
Measuring Disappearance

- Mass-squared splitting shifts the ‘dip’
- Mixing angle determines the depth of the ‘dip’

\[ \Delta m^2 = 2.46 \times 10^{-3} \text{ eV} \]
\[ \Delta m^2 = 2.52 \times 10^{-3} \text{ eV} \]
\[ \Delta m^2 = 2.32 \times 10^{-3} \text{ eV} \]
Long baseline experiments study two oscillation channels:

- Muon neutrino disappearance
  \[ \nu_\mu \rightarrow \nu_\mu \]

- Electron neutrino appearance
  \[ \nu_\mu \rightarrow \nu_e \]
Electron Neutrino Appearance

- Electron neutrino appearance probability has \textbf{CP odd} term.
  - Sign flip between matter and antimatter.

\[
P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4E} \\
(+)- \left[ \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \right. \\
\times \sin \frac{\Delta m_{21}^2 L}{4E} \sin^2 \frac{\Delta m_{32}^2 L}{4E} \left. \sin \delta_{CP} \right]
\]

+ (CP-even, solar, matter effect terms)
Electron Neutrino Appearance

- Electron neutrino appearance probability has ‘CP odd’ term.
  - Sign flip between matter and antimatter.

\[
P(^{-}\nu_{\mu} \rightarrow ^{-}\nu_{e}) \simeq \sin^{2} \theta_{23} \sin^{2} 2\theta_{13} \sin^{2} \frac{\Delta m_{32}^{2} L}{4E} \\
\times \left[ \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \right] \\
+ \left( \text{CP-even, solar, matter effect terms} \right)
\]
Electron Neutrino Appearance

- Electron neutrino appearance probability has ‘CP odd’ term.
  - Sign flip between matter and antimatter.

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E} \]

What is the value of \( \delta_{CP} \)?

\[ P(\nu_\mu \rightarrow \nu_e) + \text{(CP-even, solar, matter effect terms)} \]

- T2K B.F. 2018, \( L=295 \text{ km} \), \( \delta_{CP} = 0 \)
  - No CPV

- \( \delta_{CP} = \frac{3\pi}{2} \)
  - Maximal CPV
Electron Neutrino Appearance

- Electron neutrino appearance probability has ‘CP odd’ term.
  - Sign flip between matter and antimatter.

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4E} + (\text{CP-even, solar, matter effect terms})
\]

\[
(+)^- \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13}
\times \sin \frac{\Delta m_{21}^2 L}{4E} \sin^2 \frac{\Delta m_{32}^2 L}{4E} \sin \delta_{CP}
\]

Most sensitive to $\delta_{CP}$ when other parameters are known precisely.
Appearance on T2K and NOvA

Number of neutrinos = Flux • Oscillation probability

\[ \Delta m^2_{12} = 7.37 \times 10^{-5} \text{ eV} \]
\[ \Delta m^2_{32} = 2.46 \times 10^{-3} \text{ eV} \]
\[ \sin^2(\theta_{12}) = 0.297 \]
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\[ \delta_{CP} = 0 \]

L = 295 km

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\[ \sin^2(\theta_{12}) = 0.297 \]
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\[ \sin^2(\theta_{23}) = 0.526 \]
\[ \delta_{CP} = 0 \]

L = 810 km

\[ \Phi \] (Arbitrary Units)

E\(_v\) (GeV)
Neutrino and Antineutrino Appearance

NEUT 5.3.6, $\bar{\nu}_e$, T2K Best Fit, $L=810$ km

- $\delta_{CP}=0$
- $\delta_{CP}=\pi/2$
- $\delta_{CP}=\pi$
- $\delta_{CP}=3\pi/2$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Events (Arbitrary Units)

$E_\nu$ (GeV)
Neutrino and Antineutrino Appearance

NEUT 5.3.6, $\bar{\nu}_e$, T2K Best Fit, $L=810$ km

- $\delta_{CP}=0$
- $\delta_{CP}=\pi/2$
- $\delta_{CP}=\pi$
- $\delta_{CP}=3\pi/2$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Events (Arbitrary Units)

$E_\nu$ (GeV)

NEUT 5.3.6, $\nu_e$, T2K Best Fit, $L=810$ km

- $\delta_{CP}=0$
- $\delta_{CP}=\pi/2$
- $\delta_{CP}=\pi$
- $\delta_{CP}=3\pi/2$

$\nu_\mu \rightarrow \nu_e$

Events (Arbitrary Units)

$E_\nu$ (GeV)
Neutrino and Antineutrino Appearance

NEUT 5.3.6, $\bar{\nu}_e$, T2K Best Fit, L=810 km

- $\delta_{CP}=0$
- $\delta_{CP}=\pi/2$
- $\delta_{CP}=\pi$
- $\delta_{CP}=3\pi/2$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\nu_\mu \rightarrow \nu_e$

$\nu_e$ Events (Arbitrary Units)

$\bar{\nu}_e$ Events (Arbitrary Units)

NEUT 5.3.6, $\nu_e$, T2K Best Fit, L=810 km

- $\delta_{CP}=0$
- $\delta_{CP}=\pi/2$
- $\delta_{CP}=\pi$
- $\delta_{CP}=3\pi/2$

Normal Hierarchy

Inverted Hierarchy
Neutrino and Antineutrino Appearance

NEUT 5.3.6, $\bar{\nu}_e$, T2K Best Fit, L=810 km

- $\delta_{CP} = 0$
- $\delta_{CP} = \pi/2$
- $\delta_{CP} = \pi$
- $\delta_{CP} = 3\pi/2$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\nu_e$ Events (Arbitrary Units)

0 0.1 0.2 0.3 0.4
0 1 2 3 4 $E_\nu$ (GeV)

$\delta_{CP}$

Normal Hierarchy

Inverted Hierarchy

NEUT 5.3.6, $\nu_e$, T2K Best Fit, L=810 km

- $\delta_{CP} = 0$
- $\delta_{CP} = \pi/2$
- $\delta_{CP} = \pi$
- $\delta_{CP} = 3\pi/2$

$\nu_\mu \rightarrow \nu_e$

$\nu_e$ Events (Arbitrary Units)

0 0.1 0.2 0.3 0.4
0.2 0.4 0.6 $\nu_e$ Events (Arbitrary Units)

Events (Arbitrary Units)

0 0.5 1 1.5
0 1 2 3 4 $E_\nu$ (GeV)
Most sensitive to $\delta_{CP}$ if:
- Know hierarchy
- Know disappearance parameters well
- Measure $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Different characteristics due to strength of matter effect at T2K and NOvA energies.
Oscillation Physics Programs
Anatomy of an Oscillation Analysis

- Sample oscillated beam
- Infer oscillation probabilities
- Sample un-oscillated beam
- Study neutrino interaction physics

Super-Kamiokande

- Mt. Noguchi-Goro 2,924 m
- Mt. Ikeno-Yama 1,360 m

Neutrino Beam

1,700 m below sea level

295 km

J-PARC

Produce neutrino beam

Neutrino Mode Flux at ND280

$\nu_\mu$,
$\bar{\nu}_\mu$,
$\nu_e$,
$\bar{\nu}_e$
Near Detectors

- T2K Oscillation analysis: Near Detectors
  - INGRID: On-axis, ensures beam alignment
  - ND280: Off-axis near detector

- ND280
  - Magnetized: Charge and momentum measurements
    - Constrain ‘wrong sign’ backgrounds
Near detector samples separated by:
- Reconstructed pion multiplicity: N=0, 1, >1
- Detector material: CH (FGD) or CH+H2O (FGD2)

- Binned in observed lepton kinematics only.
- Both neutrino and antineutrino beam modes.
Near Detector Fit

- Near detector samples:
  - Tune neutrino interaction model
  - Tune flux prediction
Near Detector Fit

- Near detector samples:
  - Tune neutrino interaction model
  - Tune flux prediction

Near detector data-simulation comparison

Fit Free parameters
Near Detector Fit

- Near detector samples:
  - Tune neutrino interaction model
  - Tune flux prediction
- Constrain event rate uncertainties for Far detector

Near detector data-simulation comparison

Fit Free parameters

Far detector predicted event rates with oscillations

Neutrino-mode, muon-like

Neutrino-mode, electron-like
Water Cherenkov detector.

Sensitive to:
- Electrons, muons, pions

Can discriminate Cherenkov rings from:
- electrons ('fuzzy')
- muons ('sharp')
Near Detector Samples

- Fully active calorimeter detector:
  - Functionally identical to Far detector
- Select contained muon-like and electron-like samples:
  - Both neutrino and antineutrino beam modes
- Separated into sub samples based on reconstructed elasticity: $E_{\text{Hadronic}}/E_{\text{Total}}$
  - Improved sensitivity to interaction-mismodelling
  - Isolating higher resolution sub-samples (less $E_{\text{Hadronic}}$) → more disappearance shape sensitivity

Phys. Rev. Lett. 123, 151803
Near to Far Extrapolation

1. Sample near detector events
Near to Far Extrapolation

1. Sample near detector events

2. Estimate true neutrino energy spectrum with interaction model
Near to Far Extrapolation

1. Sample near detector events
2. Estimate true neutrino energy spectrum with interaction model
3. Account for far/near differences and oscillate true spectrum
1. Sample near detector events
2. Estimate true neutrino energy spectrum with interaction model
3. Account for far/near differences and oscillate true spectrum
4. Predict observed oscillated spectrum and compare for goodness of fit.
Oscillation Physics Results
Muon-like samples

- Both analysis simultaneously fit:
  - Both beam modes
  - Mu-like and e-like

- Clear oscillation shape in muon-like samples.
Muon-like samples

- Both analysis simultaneously fit:
  - Both beam modes
  - Mu-like and e-like

- Clear oscillation shape in muon-like samples.

- Different baselines, energies:
  - Complementary sensitivity
Disappearance Constraints

- NOvA provides slightly tighter constraint of mass-squared splitting
Disappearance Constraints

- T2K provides slightly tighter constraint of the mixing angle
Electron-like samples

Both experiments:
- See significant electron appearance above background
- In both neutrino and antineutrino beam modes

\[ \nu_e \]

\[ \bar{\nu}_e \]

\[ \nu_\mu \rightarrow \nu_e, \delta_{CP} = 0 \]

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e, \delta_{CP} = 0 \]

Background
Electron-like samples

- Both experiments:
  - See significant electron appearance above background
  - In both neutrino and antineutrino beam modes

4.4σ antineutrino appearance measurement

\[ \nu_e \rightarrow \nu_e, \delta_{CP} = 0 \]
\[ \bar{\nu}_e \rightarrow \bar{\nu}_e, \delta_{CP} = 0 \]

[Graphs showing data and predictions for neutrino and antineutrino modes]
Appearance Constraints

- Both analyses include $\theta_{13}$ constraint from reactor data.
Appearance Constraints

- Both analyses include $\theta_{13}$ constraint from reactor data.
Appearance Constraints

Nature 580 7803 p339-344

\[ \sin^2 \theta_{23} \]

- 68.27% confidence level
- 99.73% confidence level

\[ \delta_{CP} \]

- Normal order
- Inverted order

T2K

\[ \sin^2 \theta_{23} \]

- 1σ - 2σ - 3σ • Best fit

NH

INova

- 2σ - 3σ

\[ \delta_{CP} \]
Appearance Constraints

Nature 580 7803 p339-344
Appearance Constraints

- Overlapping $1\sigma$ regions.
Appearance Constraints

- Overlapping $1\sigma$ regions.
- Both analyses disfavor the inverted mass hierarchy.
Overlapping $1\sigma$ regions.

Both analyses disfavor the inverted mass hierarchy.

Latest T2K: First result favoring values at $3\sigma$.
- **Disfavors CP conservation at $2\sigma$**

*Nature 580 7803 p339-344*
Matter vs. Antimatter rates

- Compare expected and observed $\nu_e$ and $\bar{\nu}_e$ rates:
  - Sensitivity to $\delta_{CP}$ and Mass hierarchy
Matter vs. Antimatter rates

- Compare expected and observed $\nu_e$ and $\bar{\nu}_e$ rates:
  - Sensitivity to $\delta_{CP}$ and Mass hierarchy
Increasing $\sin^2(\theta_{23})$

- Compare expected and observed $\nu_e$ and $\bar{\nu}_e$ rates:
  - Sensitivity to $\delta_{CP}$ and Mass hierarchy

Prediction ‘1σ’ uncertainties at best fit
Increasing $\sin^2(\theta_{23})$

- Compare expected and observed $\nu_e$ and $\bar{\nu}_e$ rates:
  - Sensitivity to $\delta_{CP}$ and Mass hierarchy

Prediction ‘1σ’ uncertainties at best fit

**NH**

**IH**

NOvA Preliminary

- $\sin^2 \theta_{13} = 0.082$
- $\sin^2 \theta_{23} = 0.48$
- $\Delta m_{32}^2 = -2.54 \times 10^{-3} \text{eV}^2$
- $\Delta m_{32}^2 = +2.48 \times 10^{-3} \text{eV}^2$

2K Run 1-9c Preliminary

**Total events - antineutrino beam**

**Total events - neutrino beam**

L. Pickering

J. Wolcott, FNAL UM2019
T2K-NOvA Complementarity
T2K-NOvA Complementarity

- Complementary sensitivities:
  - Degenerate dcp/hierarchy values for one baseline not for the other.

\[
\sin^2 \theta_{23} = 0.48 \\
\Delta m^2_{32} = -2.54 \times 10^{-3} \text{eV}^2
\]

\[
\sin^2 \theta_{23} = 0.56 \\
\Delta m^2_{32} = +2.48 \times 10^{-3} \text{eV}^2
\]
T2K-NOvA Complementarity

- Complementary sensitivities:
  - Degenerate dcp/hierarchy values for one baseline not for the other.
  - Degenerate for T2K but not NOvA.

**Preliminary**

**PTEP2015, 043C01**

Degenerate for T2K but not NOvA
T2K-NOvA Complementarity

- Complementary sensitivities:
  - Degenerate dcp/hierarchy values for one baseline not for the other.
  - Degenerate for NOvA but not T2K+NOvA

Wrong MH rejection

Degenerate for NOvA but not T2K+NOvA
Joint Fit

- Joint fit with access to full likelihood allows for:
  - more robust statistical treatment,
  - correlations between important systematic parameters.
Joint Fit

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  - more robust statistical treatment,
  - correlations between important systematic parameters.

- Interaction model is a good place to check...
Joint Fit

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  - more robust statistical treatment,
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- Interaction model is a good place to check...

**NEUT 5.3.6, $\nu_\mu^{16}$O**

- CC Incl
- CC $0\pi$
- CC $1\pi$
- CC $2+\pi$

$\Delta m^2_{21} = 7.37 \times 10^{-5}$ eV
$\Delta m^2_{32} = 2.46 \times 10^{-3}$ eV

$\sin^2(\theta_{12}) = 0.297$
$\sin^2(\theta_{13}) = 0.0214$
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$\delta_{CP} = 0$

$L = 295$ km
$E_\nu$ (GeV)
T2K-NOvA

- Joint analysis workshops on-going:
  - Four successful meetings since 2017 J-PARC and FNAL
  - Strong US-Japan support!

- Challenging joint analysis:
  - Different experimental setups
  - Different peak energy
  - Different analysis methodology

- But T2K-NOvA sensitivity is worth the challenge!
Summary

- It’s an exciting time in long baseline neutrino physics!
- Precision measurements of neutrino mixing parameters.
- Seeing sensitivity to lepton-sector CPV.
- Exciting prospect for joint analysis exploiting rich NOvA-T2K complementarity for CPV sensitivity.

Where will these be next year?
Thanks for listening

Dawn from the summit of Fuji-san
Neutrino Flavor Change In Matter

Coherent forward scattering via this $W$-exchange interaction leads to an extra interaction potential energy —

$$V_W = \begin{cases} +\sqrt{2}G_FN_e, & \nu_e \\ -\sqrt{2}G_FN_e, & \bar{\nu}_e \end{cases}$$

Fermi constant

This raises the effective mass of $\nu_e$, and lowers that of $\bar{\nu}_e$.

The fractional importance of matter effects on an oscillation involving a vacuum splitting $\Delta m^2$ is —

$$\frac{\sqrt{2}G_FN_e}{\Delta m^2/2E} \equiv x .$$

The matter effect —
- Grows with neutrino energy $E$
- Is sensitive to $\text{Sign}(\Delta m^2)$
- Reverses when $\nu$ is replaced by $\bar{\nu}$

This last is a “fake CP violation” that has to be taken into account in searches for genuine CP violation.
Oscillation Results Backup
T2K Exposure

Constraint
Nature 580 7803 p339-344

Search for CPV
Phys. Rev. Lett. 121,171802

Observation
Phys. Rev. Lett. 112, 061802

Indication
Phys. Rev. Lett. 107, 041801

This Talk!

Accumulated POT

\( \times 10^{20} \)

23 Jan 2010 - 12 Feb 2020
POT Total: \( 3.64059 \times 10^{21} \)
(maximum power 522.627 kW)

\( \nu \) mode: \( 1.99006 \times 10^{21} \) (54.7%)
\( \bar{\nu} \) mode: \( 1.65053 \times 10^{21} \) (45.3%)
NOvA Exposure

758 kW peak hourly avg: currently highest in the world

J. Wolcott, FNAL UM2019
- Main T2K detectors 2.5° off-axis with respect to the beam:
  - Kinematics of boosted pion decays result in a finer beam width, peaked around ideal L/E.

- Uncertainties dominated by hadron-production:
  - Simulation tuned to NA61/SHINE hadron-production data.
  - Currently ~10% uncertainty in the beam peak.
N.B. Each contour is a separate fit for T2K: (global fit disfavors IH to 1σ)
Oscillation Results: Sources of Error

- Neutrino interaction uncertainties large for both experiments
NOvA Oscillation Details
Event Displays

Muon neutrinos in *both* (functionally identical) detectors:

![Muon neutrinos diagram](image)

Electron neutrinos in *both* (functionally identical) detectors:

![Electron neutrinos diagram](image)
Selection

Input Image

Learned variations on the original image

\[ \nu_e, \nu_\mu, \text{bKnds} \]
T2K Oscillation Details
Main T2K detectors 2.5° off-axis with respect to the beam:
- Kinematics of boosted pion decays result in a finer beam width
- 0.6 GeV peak energy gives maximum oscillation signal @ 295 km

Uncertainties dominated by hadron-production:
- Simulation tuned to NA61/SHINE hadron-production data.
- Current: Latest `thin target' analysis: ~10% uncertainty at peak energy
- New: `replica target' tune to reduce uncertainty by a factor of 2.
ND280

- 2.5° off axis: Sees similar neutrino flux as far detector (without oscillations).
- Magnetized: Charge and momentum measurements
  - Constrain ‘wrong sign’ backgrounds ($\bar{\nu}$ in neutrino mode, $\nu$ in antineutrino mode)
- FGD used as the neutrino target:
  - Active CH target + passive water target.
- Time Projection Chambers:
  - Good momentum/PID for charged final state particles.
• 2.5° off axis: Sees similar neutrino flux as far detector (without oscillations).

• Magnetized: Charge and momentum measurements
  ○ Constrain ‘wrong sign’ backgrounds
    ($\bar{\nu}$ in neutrino mode, $\nu$ in antineutrino mode)

• FGD used as the neutrino target:
  ○ Active CH target + passive water target.

• Time Projection Chambers:
  ○ Good momentum/PID for charged final state particles.

• P0D: Specialized $\pi^0$ detector

• ECal: PID & escaping energy sampling
Near detector Flux/XSec Correlations

ND280 constraint
Predicted Event Rates $p/\theta$

- Nuebar, 1Re
- Nu-mode (Nue), 1Re
- Nu-mode (Nue), 1Re+1De
Disappearance Samples/Parameters

- Data
- Best-fit spectrum

\[ V_\mu \quad \bar{V}_\mu \]

Events/(0.05 GeV)

Ratio to no osc

Reconstructed neutrino energy (GeV)

\[ \Delta m^2 \]\n
Normal Hierarchy, 90% CL

T2K Run 1-9d Preliminary

- 90% CL
- 68% CL
- Best-fit

Normal
- Inverted

\[ \sin^2(\theta_{23}) \]

\[ 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \]

\[ 2.2 \quad 2.3 \quad 2.4 \quad 2.5 \quad 2.6 \quad 2.7 \quad 2.8 \]
Electron-like samples

- CP conserving values lie outside the $2\sigma$ contour for both bayesian and hybrid-frequentist analyses.
dcp/th13 contours
Oscillation Fit: Bi-event rate

- Appearance analysis is statistically limited:
  - Minimal spectral information
  - ‘Bi-event’ plot depicts preference for NH, $\delta_{cp} = -\pi/2$

- Observed $\bar{\nu}_e/\nu_e$ near edge of expected region given disappearance fit and PMNS oscillations.

- Excited to see more data:
  - Statistical fluctuation?
  - Modelling problem?
  - Something more exotic…?

![Graph showing oscillation fit with predictions and observations.]

**Prediction ‘1σ’ uncertainties at best fit**

**Observation**

$\sin^2(\theta_{23})$
Neutrino–Matter Interactions
But, don’t observe the flux: see final states of neutrino--matter interactions.

Problematic energy range required by L/E.

Antineutrino cross-section $\sim \frac{1}{3}$ neutrino.
Measuring Oscillations: Events

- Cross-section is non-linear near process ‘turn on’:
  - Event spectrum shape differs from flux shape in a non-trivial way.

- $E_\nu$ spectrum of interacting neutrinos still has characteristic oscillation shape:
  - If flux and cross-sections are well understood we can infer oscillation probabilities.
Measuring Oscillations: Observables

- But, don’t observe $E_{\nu}$ ...
- Reconstruct from observables:
  - Can look for oscillation signature in any observable, but some Erec is most intuitive
  - e.g.
    \[ E_{\text{rec}}^{\text{QE}} = \frac{2M_N E_\ell - M_\ell^2 + M_{N'}^2 - M_N^2}{2 (M_N - E_\ell + |\vec{p}_\ell| \cos (\theta_\ell))} \]
    - Unbiased energy reconstruction from just charged lepton for true CCQE events only:
    - Any non-CCQE get significant ERec. bias.
- Can only infer oscillation probabilities correctly if ‘feed down’ is well modelled.
What’s Important for T2K

- Analyses rely strongly on the modelling of $E_{\nu} \leftrightarrow E_{\text{Rec}}$.

- Turns out nuclear physics is hard:
  - CCQE Axial form-factor
  - W-propagator screening
  - Multi-nucleon processes (2p2h)
  - Final state interactions (e.g. $\pi$ absorption)
  - Nuclear potential

- On T2K: Focus on modelling $0\pi$ final states:
  - Mostly from CCQE+2p2h and $1\pi$ production with ‘stuck’ pion.
- Fit nucleon-level processes to historic bubble chamber data
  - ~ Free from nuclear effects.
- Dipole form is often used for the Axial form factor, \( F_A (Q^2) = F_A (0) / (1 + Q^2/M_A^2)^2 \)
  - Single free parameter \( M_A \): Strong constraint at low \( Q^2 \) causes over constraint at high \( Q^2 \).
  - Aim to include in T2K OA 2019.
‘RPA’: W Propagator Screening

- CCQE suppression from nuclear screening of W-propagator.
- T2K parameterize uncertainty as piecewise 1D function in $Q^2$.
  - Post-fit shape doesn’t resemble calculation shape...
- Theoreticians not in agreement that RPA is so important with better nuclear model: c.f. GiBUU

Multi-nucleon Interactions

- Scattering from bound nucleon-nucleon pairs within the nucleus: **different** $E_v \leftrightarrow E_{\text{Rec}}$.
- Not possible to study in isolation, will always also have:
  - True CCQE
  - CC1pi with missed pion
  - Other nuclear effects
- Current multi-nucleon models improve experimental agreement, but some way still to go.
Effect on Oscillation Analysis

- Want to check how biased the results might be if the wrong multi-nucleon model was chosen:
  - Assign uncertainty to QE-like/Δ-like nature of multi-nucleon interaction.
  - Run oscillation analysis with ‘fake data’ generated with an alternate model.

Near detector fit prefers between nominal and Δ-like
Lepton-Hadron Correlations

- Investigate lepton-hadron correlations.
- Two recent approaches:
  - Transverse imbalance
  - $q_0/q_3$ reconstruction
- Hard to use directly in OA:
  - Existing models can’t be bent to fit with current freedom...
  - Build ‘fake data’ informed by these results and use to test OA robustness.
Energy associated with liberating struck nucleon from nuclear potential

A. Bodek’s re-analysis found that the default NEUT value was poor [arXiv:1801.0797]

For 2018 T2K OA, a fit to mock-data with a large shift in E_b was used to assess uncertainty
   ○ Largest single source of error.

In the future, a smaller prior from A. Bodek’s analysis will be used.
Baby-MIND
**T2K Cross-section Results**

<table>
<thead>
<tr>
<th>Analysis Type</th>
<th>Description</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ CCInc $C^{12}$</td>
<td>(2013)</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$ NCQE $O^{16}$</td>
<td>(2014)</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$ CCInc $C^{12}$</td>
<td>(2014)</td>
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</tr>
<tr>
<td>$\nu_e$ CCInc $Fe^{56}/C^{12}H$</td>
<td>(2014)</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$ CCQE $C^{12}$</td>
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<td></td>
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<tr>
<td>$\nu_e$ CCInc $Fe^{56}$</td>
<td>(2015)</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$ CCInc $C^{12}H$</td>
<td>(2016)</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$ CC$1\pi$ $H_2O^{16}$</td>
<td>(2016)</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$ CC Coherent $1\pi$ $C^{12}$</td>
<td>(2017)</td>
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</tr>
<tr>
<td>$\nu_e$ CC$0\pi$ $H_2O^{16}$</td>
<td>(2017)</td>
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<tr>
<td>$\nu_e$ CC$0\pi$ $C^{12}H$</td>
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<td>$\nu_e$ CC$0\pi$ $C^{12}H$</td>
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<td>$\nu_e$ CC$1\pi$ $H_2O^{16}$</td>
<td>(2019)</td>
<td></td>
</tr>
</tbody>
</table>

**ND280 Analyses**

![ND280 Analyses](image)

**INGRID Analyses**
T2K Cross-section Results

- $\nu \mu$ CCInc $^{12}$C (2013)
- $\nu \mu$ NCQE $^{16}$O (2014)
- $\nu e$ CCInc $^{12}$C (2014)
- $\nu \mu$ CCInc $^{56}/^{12}$C$^{12}$H (2014)
- $\nu \mu$ CCQE $^{12}$C (2014)
- $\nu \mu$ CCQE $^{12}$C (2015)
- $\nu \mu$ CCInc $^{56}$Fe (2015)
- $\nu \mu$ CC$^{12}$H (2016)
- $\nu \mu$ CC$^{12}$H (2016)
- $\nu \mu$ CC$^{12}$H (2017)
- $\nu \mu$ CC Coherent $^{12}$C (2017)
- $\nu \mu$ CC$^{12}$H (2018)
- $\nu \mu$ CC0$\pi$ $^{12}$C$^{12}$H (2018)
- $\nu \mu$ CCInc $^{12}$C (2018)
- $\nu \mu$ CCInc P0D (2018)
- $\nu \mu$ CCInc $^{12}$H $^{16}$Fe (2019)
- NC $1\gamma$ $^{12}$H (2019)

ND280 Analyses

INGRID Analyses
Focus 1: CCInc Expanded Phase Space

- Previous ND fit only use **Forward** sample
  - Expanded PS better matches SK $4\pi$ acceptance.
  - Cross-section work directly improved oscillation analysis sample.
Focus 2: CC0π Transverse Variables

- **CC0π**: Dominant process at T2K energies:
  - Measuring lepton-hadron correlations probes relevant nuclear physics:
    - Oscillation measurements assume Observable $\equiv$ True energy relationship
    - Unknown nuclear effects distort this $\Rightarrow$ biased oscillation parameters
  - Analysis careful to reduce interaction model dependence:
    - Signal defined by nuclear-leaving particles.
    - Restricted signal phase space.

New Cross-section Results

- Newly approved results:
  - $\nu_{\mu}$ CC1$\pi^+$ CH
  - $\nu_{\mu}/\bar{\nu}_{\mu}$ CC0$\pi$ CH
  - $\nu_{\mu}$ CC1$\pi^+$ P0D
  - $\nu_{e}/\bar{\nu}_{e}$ CCInc CH
    - First $\nu_e$ since BC era!
  - $\nu_{\mu}$ CC0$\pi$ C/O
  - NCQE at SK!
  - + many more in earlier stages.
- T2K analysers developing and deploying:
  - Novel analysis techniques
  - Statistically robust data publication methodologies
WAGASCI and Baby-MIND

- **WAGASCI**:  
  ○ Water/Scintillator detector  
  ○ Can run water-out for CH subtraction  
  ○ One module on-axis and one at 1.5° off axis.

- **Baby-MIND**:  
  ○ Compact magnetised iron plate and scintillator detector  
  ○ Ranging, charge, and momentum
See Hiro's talk for more about the future!
SK-Gd

- Super-K deep cleaned in preparation for Gadolinium doping.
- Much improved efficiency for neutron capture:
  - Sensitivity to supernova relic neutrinos
  - Statistical separation of neutrino/antineutrino rate
  - Many unknown interaction effects: total cross-section, FSI, ...
- **New!** T2K-SK NCQE cross-section measurement:
  - Neutron-producing background process for supernova relics and coincidence with charged current oscillation signal events.
ND280 Upgrade

- POD being replaced for T2K-II
- New 3D scintillator detector + horizontal TPCs:
  - Improved acceptance
    - High angle
    - Low momentum (esp. protons)

SuperFGD

Efficiency

arXiv:1901.03750 [physics.ins-det]
T2K-II and J-PARC Beam upgrade

- T2K has recorded $3.16 \times 10^{21}$ POT
  - T2K original POT quota: $7.8 \times 10^{21}$
- T2K-II to take: $20 \times 10^{21}$
- Continued rich physics program and improved oscillation sensitivity until Hyper-K