Contents

• Introduction:
  • Neutrino mixing
  • Two leading accelerator-based long-baseline experiments: T2K and NOvA
  • Recent oscillation results from T2K and NOvA
  • (Near) future prospects
• Summary
Neutrino Mixing

- Neutrino flavor (weak) eigenstates and mass eigenstates are mixed
  \[ |\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \]

- Neutrinos change their flavor as they travel (neutrino oscillation)
- Natural interferometer to explore fundamental nature of neutrinos

Two neutrino case:

\[ P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu(t) \rangle|^2 = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

\[ \theta \quad : \text{mixing angle} \]
\[ \Delta m^2 \quad : \text{mass squared difference} \]
\[ L \quad : \text{the distance traveled} \]
\[ E \quad : \text{the energy of neutrino} \]

Figure taken from J. P. Ochoa’s presentation at Neutrino2018
Neutrino Mixing

All the three angles are finally observed!

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \times \begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix} \times \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[\theta_{23} \approx 45^\circ\]
Atmospheric \(\nu\)
Accelerator \(\nu\)

\[\theta_{13} \sim 9^\circ\]
 reactor \(\nu\)

\[\theta_{12} \approx 35^\circ\]
Solar \(\nu\)
Reactor \(\nu\)

\[\Delta m^2_{32} \sim \Delta m^2_{31} \sim 2.5 \times 10^{-3} \text{ eV}^2\]

\[\Delta m^2_{21} \sim 7.5 \times 10^{-5} \text{ eV}^2\]

Still many open questions:

- What is the CP-violation phase, \(\delta\) ?
- What is the absolute mass scale/ordering?
- What is the origin of neutrino mass?
- Are there any extra spices?
Accelerator-based long-baseline neutrino oscillation experiments

- High-intensity muon (anti-)neutrino beam produced by smashing protons to fixed targets
- Near detectors to constrain the beam flux, and measure oscillation at the far detectors
- Both uses off-axis narrow-band neutrino beam.

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Peak energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2K</td>
<td>295 km</td>
<td>~ 600 MeV</td>
</tr>
<tr>
<td>NOvA</td>
<td>810 km</td>
<td>~ 2 GeV</td>
</tr>
</tbody>
</table>
Oscillation signatures

Example for the T2K beam

\( v_\mu \) disappearance

\[ \nu_\mu \rightarrow \nu_\mu = \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \]

\( 2.5^\circ \text{ Off-axis } \nu_\mu \text{ flux} \)

- Precision measurement of \( \sin^2 2\theta_{23} \) and \( |\Delta m^2_{32}| \)

- Can test CPT symmetry

\( v_e \) appearance

\[ \nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]

- Sensitivity to \( \sin^2 2\theta_{13} \), CP violating phase \( \delta \), \( \theta_{23} \) octant, and mass ordering through the matter effect

- Important to have multiple experiments to disentangle impacts of those parameters
Experimental apparatus and performance
T2K neutrino beamline at J-PARC

- 30 GeV protons extracted from J-PARC Maing Ring smashes a graphite target

- Secondary $\pi^+/-$ are focused by three magnetic horns, and decay into $\mu^+/-$ and $\nu_\mu$ in the decay volume

- Muon detector monitors beam stability.

Can switch neutrino mode and anti-neutrino mode by switching the horn current.
The T2K Beam

- Delivered beam (until May 2018)
  - $1.51 \times 10^{21}$ POT neutrino mode (Forward Horn Current)
  - $1.65 \times 10^{21}$ POT antineutrino mode (Reverse Horn Current)
- Used for the latest oscillation analysis:
  - $1.49 \times 10^{21}$ POT neutrino mode
  - $1.12 \times 10^{21}$ POT antineutrino mode
T2K near complex

T2K Near Detector complex consists of off-axis (ND280) and on-axis (INGRID) detectors

- **ND280**
  - Measures flux at SK direction before oscillation
  - Detector placed in 0.2 T magnetic field
  - Tracker consists of 2 fine-grained detectors (FGDs) and 3 TPCs
  - Plastic and Water targets

- **INGRID**
  - Measures beam profile and direction
  - Array of 9-ton iron-scintillator sandwich detectors
T2K ND280 data samples

- 14 total ND280 data samples used by oscillation analysis fit
- $\nu$-mode (FHC)
  - sort by $\pi^+$ multiplicity
  - 2 fine-grained detectors (FGDs) (C,O)
    ➡ 6 samples
- $\bar{\nu}$-mode (RHC)
  - sort by muon charge
  - sort by number of tracks
  - 2 FGDs (C,O)
    ➡ 8 samples

Wrong sign backgrounds
ND280 data fitting

- The 14 ND 280 samples are used to constrain neutrino flux and cross-section

- After the fit, the flux and cross-section uncertainty at the far detector reduced to ~5% from ~15%

- Also measures neutrino interaction cross-sections
Super-Kamiokande (T2K far detector)

- 50-kton water Cherenkov detector
- Overburden: 2700 mwe
- Inner Detector covered by > 11000 20" PMTs (40% photo coverage)
- Outer detector equipped with ~2000 8" PMTs and act as veto
- Can detect neutrinos for wide energy range
  - Solar neutrinos
  - Supernova neutrinos
  - Atmospheric/Accelerator neutrinos
- Operational since 1996

50-kton water Cherenkov detector

- Overburden: 2700 mwe
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- Can detect neutrinos for wide energy range
  - Solar neutrinos
  - Supernova neutrinos
  - Atmospheric/Accelerator neutrinos
- Operational since 1996
Super-K event samples

- Utilizes ring pattern to separate muons and electrons

μ-like event

- e-like event
NOvA beam delivery

- NuMI beam running at 700 kW since Jan 2017
- Recorded POT by April 2018:
  - Neutrino mode: $8.85 \times 10^{20}$ POT
  - Antineutrino mode: $6.9 \times 10^{20}$ POT
NOvA Near and Far detectors

- Uses the same technology for both near and far detectors
  - PVC extrusion + Liquid scintillator
  - Layered planes of orthogonal views with 6-cm cells. Readout via WLS fibers to APDs.
- Near detector (0.3 kton)
  - 1 km from source, 100 m depth
- Far detector (14 kton)
  - 810 km from source, on the surface, 3 m.w.e. overburden.
Neutrino events at NOvA

Utilizes Convolutional Neural Networks (CNN) for particle classification
Oscillation Analysis Results
T2K disappearance analysis

\[ \nu_\mu \]

1.49e21 POT

\[ \bar{\nu}_\mu \]

1.12e21 POT

\[ \Delta m^2_{32} (\text{NH}), \Delta m^2_{31} (\text{IH}) (\text{eV}^2) \]

\[ \text{Data fit with reactor constraint} \]

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

\[ \begin{array}{cc}
\text{NH} & \text{IH} \\
0.536^{+0.031}_{-0.046} & 0.536^{+0.031}_{-0.041} \\
\end{array} \]

\[ |\Delta m^2| \]

\[ \begin{array}{cc}
2.434 \pm 0.064 & 2.410^{+0.062}_{-0.063} \\
\end{array} \]

T2K result consistent with maximal mixing (\( \theta_{23} = 45^\circ \))
NOvA disappearance analysis

**Reconstructed Neutrino Energy (GeV)**

- **FD Data**
- **Prediction**
- **1-σ syst. range**
- **Wrong Sign:ν\(_\mu\)CC**
- **Total bkg.**
- **Cosmic bkg.**

**Events / 0.1 GeV**

- **Neutrino beam**
- **Antineutrino beam**

**Allowed Oscillation Parameters**

- **Best fit**
- **NH Lower octant**
- **NH Upper octant**
- **IH Lower octant**
- **IH Upper octant**

**Normal Hierarchy 90% CL**

- **NOvA**
- **MINOS 2014**
- **T2K 2017**
- **IceCube 2017**
- **SK 2017**

- **Δm\(^2\)_{32} (10^{-3} eV^2)**

- **sin^2θ_{23} = 0.58±0.03 (UO)**

- **Δm\(^2\)_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3} eV^2**

**Best fit: Normal Hierarchy**

- **δ_{CP} = 0.17π**

**90% CL region compatible with other experiments**

- **Prefer non-maximal mixing at 1.8σ**

Mayly Sanchez, Neutrino 2018
DOI: 10.5281/zenodo.1286758
T2K appearance samples

Three appearance samples used for the fit:
(1π identified with additional decay-e)

1Ring $\nu_e + 0$ decay-e

1Ring $\nu_e + 1$ decay-e ($\pi$)

1Ring $\bar{\nu}_e + 0$ decay-e

---

Sample | Prediction | Data
---|---|---
| | $\delta_{CP} = -\pi/2$ | $\delta_{CP} = 0$ | $\delta_{CP} = \pi/2$ | $\delta_{CP} = \pi$
| 1Ring $\nu_e$, 0 decay-e | 73.8 | 61.6 | 50.0 | 62.2 | 75
| 1Ring $\nu_e$, 1 decay-e | 6.9 | 6.0 | 4.9 | 5.8 | 15
| 1Ring $\bar{\nu}_e$, 0 decay-e | 11.8 | 13.4 | 14.9 | 13.2 | 9

Compared with the predictions, observed more events in the neutrino mode, less events in the antineutrino mode

Morgan Wascko, Neutrino 2018
DOI: 10.5281/zenodo.1286752
T2K Appearance results

DATA FIT

Data fit w/ reactor constraints

CP conserving values excluded by > 2σ for both hierarchy assumptions

Morgan Wascko, Neutrino 2018
DOI: 10.5281/zenodo.1286752
• Prior probability assumption of $\delta_{\text{CP}}$ does not affect $2\sigma$ exclusion of CP conservation

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2\theta_{23} \leq 0.5$</th>
<th>$\sin^2\theta_{23} &gt; 0.5$</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH ($\Delta m_{32}^2 &gt; 0$)</td>
<td>0.204</td>
<td>0.684</td>
<td>0.888</td>
</tr>
<tr>
<td>IH ($\Delta m_{31}^2 &lt; 0$)</td>
<td>0.023</td>
<td>0.089</td>
<td>0.112</td>
</tr>
<tr>
<td>SUM</td>
<td>0.227</td>
<td>0.773</td>
<td>1</td>
</tr>
</tbody>
</table>

• Bayes factor for NH/IH is 7.9

• ~50% more antineutrino data to be included soon
NOvA appearance samples

**Neutrino mode:**
53 events observed w/ 15 expected backgrounds

**Antineutrino mode:**
18 events observed w/ 5.3 expected backgrounds

> 4σ evidence of electron antineutrino appearance
NOvA $\delta_{cp}$ and NH results

**Graph:**
- **NOvA FD:**
- **8.85x10^{20} POT equiv $\nu + 6.9x10^{20} POT \bar{\nu}$**

**Best fit:** Normal Hierarchy
- $\delta_{cp} = 0.17\pi$
- $\sin^2 \theta_{23} = 0.58 \pm 0.03$ (UO)
- $\Delta m_{32}^2 = (2.51^{+0.12}_{-0.08}) \times 10^{-3}$ eV$^2$

**Prefer NH by 1.8$\sigma$**
**Exclude $\delta = \pi/2$ in the IH at > 3$\sigma$**
T2K and NOvA appearance samples

**T2K**

Antineutrino mode 1Re candidates

- \( \sin^2\theta_{23} = 0.50, 0.45, 0.55 \)
- \( \Delta m_{32}^2 = 2.44 \times 10^{-3} \text{eV}^2/\text{c}^4 \)
- \( \Delta m_{13}^2 = 2.41 \times 10^{-3} \text{eV}^2/\text{c}^4 \)

- \( \delta_{\text{CP}} = \pi \)
- \( \delta_{\text{CP}} = \pm \pi/2 \)
- \( \delta_{\text{CP}} = 0 \)
- \( \delta_{\text{CP}} = -\pi/2 \)

- syst err
- stat + syst err
- Data

**NOvA**

Total events - antineutrino mode

- NOvA FD
- \( 9.48 \times 10^{20} \text{ POT (v)} \)
- \( 6.91 \times 10^{20} \text{ POT (v)} \)

- \( \sin^2 \theta_{23} = 0.082 \)

- \( \sin^2 \theta_{23} = 0.59 \)

- \( \Delta m_{32}^2 = -2.55 \times 10^{-3} \text{eV}^2 \)
- \( \Delta m_{32}^2 = +2.50 \times 10^{-3} \text{eV}^2 \)

- \( \delta_{\text{CP}} = 0 \)
- \( \delta_{\text{CP}} = \pi/2 \)
- \( \delta_{\text{CP}} = \pi \)
- \( \delta_{\text{CP}} = 3\pi/2 \)

Stay tuned for how those evolves with more statistics and improved analyses!
Near future prospects

- Joint T2K-NOvA analysis
- T2K extension and its near-detector upgrade
- Super-K upgrade with Gd loading
Joint T2K-NOvA analysis

• Aiming to produce full joint oscillation analysis by 2021

• Preparing for a joint working group; three workshops held so far.

T2K and NOvA collaborations to produce joint neutrino oscillation analysis

January 30, 2018

The NOvA and T2K Collaborations are working towards the formation of a joint working group to enhance the measurements of neutrino oscillation parameters made by each Collaboration individually. The projected timescale of the NOvA-T2K working group is for production of a full joint neutrino oscillation analysis by 2021.
T2K extension and upgrades

- **T2K phase-II**
  - Proposal to collect $20 \times 10^{21}$ POT (stage-1 approved by KEK/J-PARC)
  - Will have $> 3\sigma$ sensitivity for CPV
- Beam upgrade towards 1.3 MW beam power
- **Near-detector upgrade**
  - Required for further reducing systematics down to $\sim 4\%$
  - Aiming for installation in 2021
Super-K upgrade w/ Gd loading

SK-Gd project

- Loading Gd to the SK pure water to enhance neutron detection capability
  - ~90% Gd capture probability with 0.1% Gd loading
- Primary goal is to detect supernova relic neutrinos
- Could also benefit T2K with:
  - Improved neutrino-antineutrino separation
  - Improved energy reconstruction
  - Improved measurement neutrino interaction

\[ \bar{\nu}_e \rightarrow p + e^+ + Gd, \Delta T \sim 30\mu s, \text{Vertices within 50cm} \]

\[ \bar{\nu}_e \rightarrow p + e^+ + \gamma + Gd, 8\text{ MeV} \]

SK-Gd status

• To realize SK-Gd, a major refurbishment of the SK tank started on May 31, 2018
• The tank was opened for the first time in 12 years for:
  • Leak fixing
  • Water piping upgrades
  • PMT replacements
• Major part of refurbishment finished and started filling pure water again
• New water system for SK-Gd is now being commissioned
• Planning ongoing for initial loading of 0.01% Gd (corresponds to ~10 tons of Gd$_2$(SO$_4$)$_3$)
Summary

• Discussed recent results from the two leading long-baseline neutrino oscillation experiments: T2K and NOvA

• Interesting hints for $\delta_{cp}$, MH and $\theta_{23}$ octants from both experiments.

• A lot more to come, including:
  • NOvA-T2K joint analysis
  • T2K upgrades
  • Gd loading to Super-K
  • And many more!

*Stay tuned for the future results!*