Recent Neutrino Oscillations Results from the T2K and NOvA Experiments

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University of Pittsburgh
(Representing the T2K collaboration)
Outline

- Motivation
- T2K and NOvA Experiments
- Oscillation Results:
  - Muon (+Anti-)Neutrino Disappearance
  - Electron (+Anti-)Neutrino Appearance
  - Joint Fits
- Prospects, Outlook and Summary
3-Flavor Mixing

- 3-flavor mixing describes (almost) all neutrino oscillation phenomena (3 mixing angles, 2 independent mass splittings, 1 CPV phase)

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{+i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Atmospheric & accelerator:
\[\theta_{23} \sim 45^\circ\]
\[(\Delta m_{23}^2) \sim 2.4 \times 10^{-3} \text{ eV}^2\]

Interference:
\[\theta_{13} \sim 9^\circ\] and \[\delta_{CP} = ??\]

Solar & reactor:
\[\theta_{12} \sim 34^\circ\]
\[(\Delta m_{12}^2) \sim 8 \times 10^{-5} \text{ eV}^2\]

Muon neutrino disappearance \((\nu_\mu \rightarrow \nu_\mu)\):

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

Electron neutrino appearance \((\nu_\mu \rightarrow \nu_e)\):

\[P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E}\right) \left[1 + \frac{2a}{\Delta m_{31}^2} (1 - 2\sin^2 \theta_{13})\right] + \sin 2\theta_{12} \sin 2\theta_{13} \sin \theta_{13} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E}\right)\]

CPU violating

\[(P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \delta \text{ turns into } -\delta \text{ and } a \text{ to } -a \text{ (“a” matter effect term)}\]

Depends on sign of mass difference:
\(i.e.\) Mass Ordering
Oscillation Primer

Unoscillated
Oscillated

\[ P(\nu_\mu \rightarrow \nu_\mu) \]

Location of dip in energy: \( \Delta m^2_{32} \)
Depth of dip: \( \sin^2 \theta_{23} \)

Unoscillated
Oscillated

\[ P(\nu_\mu \rightarrow \nu_e) \]

Magnitude of peak linked to \( \sin^2 \theta_{13}, \delta_{CP}, \) and mass hierarchy
What Do We Know?

Solar+KamLAND $\rightarrow \theta_{12} \sim 34^0$

SK, MINOS, T2K, NOvA $\rightarrow \theta_{23} \sim 45^0$

Daya Bay, Reno, Double Chooz $\rightarrow \theta_{13} \sim 9^0$

(T2K: $\theta_{13} \neq 0 \rightarrow$ In Appearance Channel)

$\Delta m_{21}^2 = (7.65 \pm 0.23) \times 10^{-5} \text{ eV}^2$

Sign of the mass difference, $\Delta m_{21}^2 > 0$.

$\Delta m_{32}^2 (\approx \Delta m_{31}^2) = (2.40 \pm 0.12) \times 10^{-3} \text{ eV}^2$
What We Don't Know?

- Value CP-Violating Phase: $\delta$
- $\theta_{23}$ Maximal? Octant? ($< \text{or} > 45^0$)
- Sign of the mass difference: $\Delta m_{32}^2 = m_3^2 - m_2^2$
  - Normal Ordering (NO) > 0
  - Inverted Ordering (IO) < 0
- Are there any more $\nu$'s? (sterile)
- Are Neutrinos Dirac or Majorana?
- Absolute Mass Scale
The T2K Experiment
(Tokai to Kamioka)

Goals:
- Study $\nu_e$ and $\bar{\nu}_e$ appearance ($\mu \rightarrow \nu_e, \bar{\mu} \rightarrow \bar{\nu}_e$): Explore $\delta_{CP}$ and $\theta_{13, 23}$
- Precision measurement of $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance: Explore $\theta_{23}$ and $\Delta m^2_{23}$
Overview of T2K: Beam

First Use of Off-axis $\nu_\mu$ Beam:
- Intense & high-quality beam (Beam direction stability < 1 mrad)
  - ~1 mrad shift corresponds to ~2% energy shift at peak
- Low-energy narrow-band beam
- Can choose between $\nu$ and $\bar{\nu}$ by changing current direction in horns
- $E_\nu$ peak around oscillation maximum (~0.6 GeV)
- Small high-energy tail → reduces feed-down background events
- $\pi, K$ production at target was measured using CERN NA61 exp.
**Beam Configurations**

- mode known as “forward horn current” (FHC) or “positive focusing” (PF)
- mode known as “reverse horn current” (RHC) or “negative focusing” (NF)

Note: More “WS” v's in RHC when compared to FHC

\( \nu \) – mode known as “forward horn current” (FHC) or “positive focusing” (PF)
\( \bar{\nu} \) – mode known as “reverse horn current” (RHC) or “negative focusing” (NF)
Neutrino fluxes

- Present flux uncertainties smaller than 8% (at peak)
- Main systematics due to the hadron interactions modeling →
  - With NA61/SHINE measurements using T2K replica target → goal <5%
At These Energies Neutrino Cross-sections are Poorly Known

- $\nu$ oscillations:
  - We are now in a period of precision neutrino oscillation measurements

  \[ P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{23}) \sin^2((1.27\Delta m^2_{23}L)/E_\nu) \]  
  (v$_\tau$ appearance example)

  - Note oscillation probability depends on $E_\nu$
    - However Experiments Calculate $E_{\text{rec}}$
    - $E_{\text{rec}}$ depends on Flux, $\sigma$, detector response, interaction multiplicities, target type, particle type produced and final state interactions: $E_{\text{rec}}$ not equal to $E_\nu$

  - Appearance Oscillation Measurements:
    - Large $\Theta_{13}$ and CP violation - systematics important
    - Need to understand backgrounds to $\nu_e$ searches:

  - Need Precision understanding of Low energy (Few GeV) $\nu_\mu$ & $\bar{\nu}_\mu$ cross sections to improve models.
Overview of T2K: Near Detectors (ND280)

On-Axis Detector (INGRID) Monitor v:
- Beam direction
- Beam Intensity

Off-Axis Detector:
- In SK Direction
- Measure:
  - $\nu$ flux
  - Cross-section measurements using water targets to reduce systematic errors on oscillation parameters

→ Used for monitoring of beam, flux constraints and systematic error reduction
The T2K Far Detector: Super-Kamiokande

- 50 kiloton Water Cherenkov detector 1 km underground
- Performance well matched to sub-GeV neutrinos
- High $\nu_e$ signal efficiency plus high $\pi^0$ rejection
  - 32 kiloton inner volume:
    - Fiducial cut (i.e. cut on vertex distance to wall) optimized for each interaction type.
- Probability to misidentify muon as electron is small
- GPS time recorded in real-time for every spill
- Associate events with J-PARC (beam)

Signal: Single-ring e-like
assumed to be CCQE

$\nu_\mu \rightarrow \nu_e \rightarrow e^- p$

Background

- intrinsic $\nu_e$
- NC $\pi^0$

$\nu_\mu \rightarrow \pi^0 \rightarrow \gamma \gamma$

$\nu_\mu \rightarrow \pi^0 \rightarrow \gamma\gamma$

1 EM Shower: 1 Fuzzy Ring
2 EM Showers: 2 or 1 Fuzzy Ring
Analyzed Data

Required beam direction stability achieved (< 1mrad)

Analyzed data (December, 2017)

→ $\nu$-mode: $14.9 \times 10^{20}$ POT
→ $\bar{\nu}$-mode: $11.2 \times 10^{20}$ POT ($\sim 50/50$)
→ Total: $26.2 \times 10^{20}$ POT

(POT – Protons on Target)

(Total delivered POT to T2K : $3.16 \times 10^{21}$)
Far Detector (SK): Event Timing

- T2K beam timing
  - Time window of \((-2\mu s, +10\mu s)\)
- Fully Contained (FC) definition
  - No signal in Outer Detector (OD)
- Fiducial volume definition:

![Event timing graph]

<table>
<thead>
<tr>
<th>Sample</th>
<th>Towall Cut</th>
<th>Wall Cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE 1-Ring e-like FHC</td>
<td>170 cm</td>
<td>80 cm</td>
</tr>
<tr>
<td>CCQE 1-Ring (\mu)-like FHC</td>
<td>250 cm</td>
<td>50 cm</td>
</tr>
<tr>
<td>CC1π 1-Ring e-like FHC</td>
<td>270 cm</td>
<td>50 cm</td>
</tr>
<tr>
<td>CCQE 1-Ring e-like RHC</td>
<td>170 cm</td>
<td>80 cm</td>
</tr>
<tr>
<td>CCQE 1-Ring (\mu)-like RHC</td>
<td>250 cm</td>
<td>50 cm</td>
</tr>
</tbody>
</table>
To extract $\nu$ oscillation parameters we need to model:

- The neutrino flux
- Neutrino interactions: $E_{\text{rec}}$ not equal to $E_{\nu}$
- Understand the performance of the near and far detectors
Flux & $\nu$ Background Constraints using ND280

- Select charged-current (CC) events in ND280
- Separate into 3 categories (CCQE, CC Resonance, CC DIS)
  - Parameters from simultaneous fit of 3 samples
  - Used for prediction of Super-K neutrino spectrum w/o oscillation

ND280 constraint provides significant reduction of uncertainty at Super-K: Increases the effectiveness of each proton on target
Oscillation Results

Disappearance (anti-)neutrino results...
(Test for CPT Violation or a search for non-standard $\nu$ interactions)

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

- $\theta_{23}$ Maximal? Octant? ($<\text{ or } > 45^0$)

Sensitive to: $\theta_{23}$, $|\Delta m^2_{31}|$ ($\sim|\Delta m^2_{32}|$)
$\nu_\mu$ ($\overline{\nu}_\mu$) event selection (Disappearance):
- Fully contained fiducial volume
- Single-ring $\mu$-like event
- $p_\mu > 200$ MeV/c
- # of decay electron $\leq 1$

243 events

102 events
The NOvA Experiment:

- **US based Long-baseline neutrino oscillation experiment:**
  - FNAL neutrino beam to Ash River, MN (on surface)
    - Off-axis neutrino beam: $<E_\nu> \sim 2$ GeV
    - $> 700$ kW beam achieved
  - Functionally identical near/far detectors (**T2K**)
    - Segmented liquid scintillator bars
      - $\rightarrow$ Different technology than T2K
  - Far: 14 kton total mass (65% active mass)
  - Data analysis based on:
    - Event classification with Convolutional Neural Network

8.9 x $10^{20}$ POT $\nu$ mode
6.9 x $10^{20}$ POT $\bar{\nu}$ mode
Disappearance

→ No obvious diff. between $\nu$ and $\bar{\nu}$ observed... And consistent with maximal mixing ($\Theta_{23} = 45^\circ$)

<table>
<thead>
<tr>
<th></th>
<th>NH</th>
<th>IH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2\theta_{23}$</td>
<td>$0.530 \pm 0.031$</td>
<td>$0.536 \pm 0.031$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m^2_{32}</td>
<td>$ (eV$^2$/c$^4$)</td>
</tr>
</tbody>
</table>

→ They observed 113 events in $\nu$ (expect 730 $\pm 38/-49$(syst.) w/o oscillations),
→ 65 events in $\bar{\nu}$ (expect 266 $\pm 12/-14$(syst.) w/o oscillations).

**Best fit:**
Normal Ordering
$\sin^2\theta_{23} = 0.58 \pm 0.03$
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \times 10^{-3} \text{ eV}^2$
→ Prefer non-maximal $\theta_{23}$ at 1.8σ
Oscillation Results

Appearance (anti-)neutrino results...

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E_\nu} \right) \left( 1 + \frac{2a}{\Delta m_{31}^2} (1 - 2\sin^2 \theta_{13}) \right) \]

\[ -\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta \sin \left( \frac{\Delta m_{32}^2 L}{4E_\nu} \right) \sin \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right) \]

\( Sensitive \ to: \ \theta_{13}, \ \delta_{CP}, \ \theta_{23}, \ \Delta m_{31}^2 \)

We measure “P” → Degeneracies...

- CP-Violating Phase: \( \delta \)
\( \nu_e (\bar{\nu}_e) \) event selection (Appearance):

- Fully contained fiducial volume
- Single-ring e-like event
- E\text{visible} > 100 \text{ MeV}, E\text{rec} < 1250 \text{ MeV}
- \# of decay electron = 0
- \( \pi^0 \) rejection cut

<table>
<thead>
<tr>
<th>( \nu_e ) CCQE</th>
<th>75</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{\nu}_e ) CCQE</td>
<td>9</td>
</tr>
<tr>
<td>( \nu_e ) CC1( \pi )</td>
<td>15</td>
</tr>
</tbody>
</table>

1-ring CCQE e-like

1-ring CC1\( \pi \) e-like

1-ring CCQE e-like

FHC

RHC

75 events

15 events (FHC)

9 events
Oscillation probabilities as a function of parameters

\( \theta_{23} \rightarrow \nu_e \) and \( \bar{\nu}_e \) appearance probabilities are affected in the same way

- \( \delta_{CP} = -\pi/2 \) → maximize \( \nu_e \) appearance, minimize \( \bar{\nu}_e \) (~30%)
- \( \delta_{CP} = \pi/2 \) → maximize \( \bar{\nu}_e \) appearance, minimize \( \nu_e \) (~30%)

Normal hierarchy → same as \( \delta_{CP} = -\pi/2 \) but smaller effect in T2K (~10%)

Inverted hierarchy → same as \( \delta_{CP} = \pi/2 \) but smaller effect in T2K (~10%)

(Errors shown for the case of \( \delta_{CP} = -\pi/2 \) and \( \sin^2 \theta_{23} = 0.5 \), NO, w/reactor constraint)

For T2K:
Expected # of events ($\nu, \bar{\nu}, \nu, \bar{\nu}$)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Predicted rates</th>
<th>Observed rates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta=0$</td>
<td>$\delta=\pi/2$</td>
</tr>
<tr>
<td>$\nu$-mode CCQE 1-ring $\mu$-like</td>
<td>268.2</td>
<td>268.5</td>
</tr>
<tr>
<td>$\nu$-mode CCQE 1-ring $e$-like</td>
<td>61.6</td>
<td>50.1</td>
</tr>
<tr>
<td>$\nu$-mode CC1$\pi$ 1-ring $e$-like</td>
<td>6.0</td>
<td>4.9</td>
</tr>
<tr>
<td>$\bar{\nu}$-mode CCQE 1-ring $\mu$-like</td>
<td>95.3</td>
<td>95.5</td>
</tr>
<tr>
<td>$\bar{\nu}$-mode CCQE 1-ring $e$-like</td>
<td>13.4</td>
<td>14.9</td>
</tr>
</tbody>
</table>

- Preference for $\delta_{CP}=-\pi/2$ → maximize $\nu_e$ appearance probability, minimize $\bar{\nu}_e$ appearance
- Larger effect in $e$-like+$1\pi$ (2.5% probability of observing 15 events when 6.9 are expected)
- For $\bar{\nu}_e$ appearance background level is $\sim$6.3 events → No strong statistical conclusion
- In $\nu$-mode deficit of $\mu$-like events → compatible with our systematic uncertainties model
Joint Fits ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$): $\delta_{CP}$ vs $\Theta_{13}$

T2K-Only

T2K Result with Reactor Constraint

- T2K results consistent with reactor results
- Data prefer maximal CPV: $\delta_{CP} = -\pi/2$
  - With reactor constraints: stronger preference for values of $\delta_{CP} \sim -\pi/2$
  - Even though statistics are small $\bar{\nu}_e$ results reinforce maximal CPV observed for $\nu_e$ data
Joint Fits ($\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$): $\delta_{\text{CP}}$ Measurement

T2K:

- NO: [-2.914, -0.642]
- IO: [-1.569, -1.158]

- 2σ interval calculated with Feldman&Cousins method
- CP conserving values (0, ±\pi) outside of 2σ region for both mass orderings
NOvA Observes:
58 (expected bkg 15) events in $\nu$
18 (expected bkg 5.3) events in $\bar{\nu}$:
> 4 $\sigma$ evidence of $\bar{\nu}_e$ appearance

Best fit: Normal Ordering
$\delta_{\text{CP}} = 0.17\pi$
$\sin^2\theta_{23} = 0.58\pm0.03$ (UO)
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08})\cdot10^{-3}$ eV$^2$

For NH disfavors T2K value for $\delta_{\text{CP}}$ but with small significance
T2K and NOvA Comparisons

- Both T2K and NOvA are studying the same physics
  - However they are using different detection technologies
    - This is a good thing

- As mentioned both measure \( P(\nu_\mu \rightarrow \nu_e) \) and \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \) but...
  - In the PMNS framework these are functions of several parameters
    - \textit{i.e.} Baseline for NOvA is 810km and 295km for T2K
    - Longer baselines have greater sensitivity to the Mass Ordering

- The joint measurements of T2K and NOvA important in untangling the physics parameters embedded in \( P(\nu_\mu \rightarrow \nu_e) \) and \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \), specifically \( \delta_{\text{CP}} \)
  - Preparing for a joint working group: Three workshops already held.
T2K Future

- JPARC expected to deliver higher power beam in the future
- T2K-II (run extension)
- Upgrade plans:
  - Near detector
  - Far detector (add Gd to SK)
    - Enhance neutron detection capability
    - Improved low energy $\bar{\nu}$ detection

$\rightarrow$ T2K phase 2 goal: reduce systematics to $\sim 4\%$
Summary and Outlook

- T2K has accumulated a total of $3.16 \times 10^{21}$ POT ($\sim$50/50 $\nu$ and $\bar{\nu}$ modes) ($\sim$40% of T2K's approved POT - Full amount expected by 2020-21)
- Joint analysis across all modes of oscillation $\nu_{\mu,e} / \bar{\nu}_{\mu,e}$ disappearance, appearance
- Constraints from near detector (ND280) measurements incorporated
- These data show a preference for maximal $\theta_{23}$ mixing, $\delta_{CP} \sim -\pi/2$ and NH
  - Manifested by “maximal” $\nu_{\mu} / \bar{\nu}_{\mu}$ disappearance, “large” $\nu_{e}$ appearance, “small” $\bar{\nu}_{e}$ appearance

- Stable beam power @485 kW achieved this year
- Approved upgrades for >750 kW operation
- A proposed extension of T2K(T2K II). In 2016 Stage I approval:
  - Accelerator and beam line upgrades to improve beam power to 1.3 MW
  - Allowing $20 \times 10^{21}$ POT to be accumulated by $\sim$2026
  - Primary goals are $>3\sigma$ sensitivity to CPV and $<2^\circ$ resolution on $\Theta_{23}$

- Healthy competition and complementarity between T2K and NOvA
- Joint analysis plans in the works

→ Stay Tuned: More oscillation results to come...
The T2K Collaboration

<table>
<thead>
<tr>
<th>Country</th>
<th>Institutes/Universities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poland</td>
<td>ETH Zurich, U. Bern, U. Geneva</td>
</tr>
<tr>
<td>France</td>
<td>CEA Saclay, LLR E. Poly., LPNHE Paris</td>
</tr>
<tr>
<td>Germany</td>
<td>Aachen U.</td>
</tr>
<tr>
<td>Russia</td>
<td>INR</td>
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<tr>
<td>Vietnam</td>
<td>IFIRSE</td>
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</tbody>
</table>

~500 members, 64 Institutes, 12 countries
Motivation

The Sakharov Conditions

Antimatter $\rightarrow$ Matter if:

1. Baryon number violation (baryon $\neq$ asymmetry)
2. Matter-antimatter asymmetry (CP Violation)
3. Departure from thermal equilibrium (preferential reaction direction)

A.D. Sakharov
1975 Nobel Peace Winner

Particle Physics
Astrophysics & Cosmology

Must Understand CP Violation

Discovery of CP Violation in Lepton Sector Critical

- Current evidence of CP violation confined to the quark sector.
  - Kaons and B-Mesons
- Need additional CP violation sector to account for observed matter-antimatter asymmetry

C.W. Chiang

Beauty in Physics
Far Detector: Particle ID

MS Small: Sharp Ring

EM Shower: Fuzzy Ring

2 EM Showers: > 1 Fuzzy Ring
Combined flux and cross section systematic uncertainties produce ~15% systematic errors in T2K's oscillation analyses.
Future Prospects: T2K II

- Presently T2K approved for $7.8 \times 10^{21}$ POT
- Projected to reach around 2020
- 1st stage of J-PARC main ring power supply upgrade approved
  - Major step in achieving > 1 MW beam power (currently 420 kW)
- T2K-II extends T2K accumulated POT to $20 \times 10^{21}$ POT
  - With further accelerator and beam-line upgrades expect 1.3 MW
  - Goal could be reached in 2026
T2K II Sensitivity

arXiv:1607.08004

**Goals:**

- ~3σ sensitivity to CP violation for favorable (and currently favored) parameters
- Precise measurement of $\theta_{23}$:
  - Octant resolution if $\theta_{23}$ at the edge of currently allowed region
  - Otherwise measure $\theta_{23}$ with a resolution of 1.7° or better
Put Title here