Latest T2K Neutrino Oscillation Results

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on behalf of the T2K Collaboration
Particles and Nuclei International Conference 2017 (PANIC2017)
Beijing, 2 September 2017
Outline

• Neutrino oscillations and the T2K experiment
• Joint oscillation analysis with $\nu_\mu$, $\nu_\mu$, $\nu_\tau$, and $\nu_e$ samples
• Summary
Neutrino Oscillations

\[ c_{ij} = \cos \theta_{ij} \]
\[ s_{ij} = \sin \theta_{ij} \]

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\begin{pmatrix}
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\nu_\tau
\end{pmatrix}
= \begin{pmatrix}
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\[ \theta_{ij} \neq 0, \delta_{CP}-\text{phase irreducible} \rightarrow \text{leptonic CP violation} \]
Neutrino Oscillations

Neutrino (flavor) oscillations depend on mixing angles, $\delta_{CP}$-phase and mass differences.

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$\theta_{ij} \neq 0$, $\delta_{CP}$-phase irreducible $\rightarrow$ leptonic CP violation

With a $\nu_\mu$ beam

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left( \sin^2 \theta_{23} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21} \right)$$

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

“CP-odd term”

$\Delta_{ij} \equiv \frac{\Delta m^2_{ij}L}{4E}$

$\Delta m^2_{ij} \equiv m^2_i - m^2_j$

* neglecting matter effects
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$\theta_{ij} \neq 0$, $\delta_{\text{CP}}$-phase irreducible $\rightarrow$ leptonic CP violation

With a $\bar{\nu}_\mu$ beam flip sign

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left( \sin^2 \theta_{23} + \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{\text{CP}} \sin \Delta_{21} \right)$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = P(\nu_\mu \rightarrow \nu_\mu) \text{ by CPT symmetry}$$

CP-odd term in appearance channels allow extraction of $\delta_{\text{CP}}$ using neutrino and anti-neutrino beams, up to $\pm 30\%$ effect at T2K

$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$

$\Delta m^2_{ij} \equiv m^2_i - m^2_j$

* neglecting matter effects
The T2K Experiment

Diagram by Kirsty Duffy

Super-Kamiokande

Japan Proton Accelerator Research Complex (J-PARC)

Mt. Noguchi-Goro
2,924 m

Mt. Ikeno-Yama
1,360 m

1,700 m below sea level

295 km

Neutrino Beam

To SK

ND280

ν

μ

π, K

Graphite target

30 GeV proton beam
The T2K Experiment

Charge selection on neutrino parents
→ \( \nu \) or \( \bar{\nu} \) mode
Crossed arrays of 9-ton iron-scintillator detectors
- Monitor neutrino beam stability and beam spatial profile
- estimate beam flux uncertainty
- stand-alone cross-section measurements
The T2K Experiment

Diagram by Kirsty Duffy
T2K off-axis near detector (ND280)
T2K off-axis near detector (ND280)

Tracker:
- FGD: Fine-Grained Detector
  1. plastic scintillator $C_8H_8$ target
  2. $C_8H_8 + H_2O$ target
- Time Projection Chamber (TPC)

- constrain beam flux and cross section for oscillation analysis
- stand-alone neutrino interaction measurements
T2K far detector: Super-Kamiokande

- 50 kt water-Cherenkov
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector
  → time and amplitude of Cherenkov light

Source: http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/image-e.html
T2K far detector: Super-Kamiokande

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\[
\begin{align*}
\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e & \quad \mu/\mu^+/e/e^+ \\
\rightarrow & \quad \text{detect propagated } \nu \text{ from J-PARC} \\
\rightarrow & \quad E_\nu \text{ rec. from } \mu/e \text{ kinematics}
\end{align*}
\]
SK event reconstruction

**NEW** since 2016 summer:
New reconstruction algorithm: fiTQun (likelihood-based)
Re-optimizing fiducial volume: ~30% increase in effective statistics
SK event reconstruction

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![Distance to wall along particle trajectory](image)

Minimum distance to wall
SK event reconstruction

NEW since 2016 summer:
New reconstruction algorithm: fiTQun (likelihood-based)
Re-optimizing fiducial volume: ~30% increase in effective statistics

- Larger Towall = finer sampling of ring = better reconstruction
- Optimize cuts accounting for statistical and systematic errors
Data collection history
(Protons-On-Target)

- Total Accumulated POT for Physics
- ν-Mode Beam Power
- ν-Mode Beam Power

Accumulated POT

Beam Power (kW)

× $10^{20}$
Data collection history
(Protons-On-Target)

Total Accumulated POT for Physics

ν-Mode Beam Power

ν-Mode Beam Power

$\times 10^{20}$

Accumulated POT

Beam Power (kW)

Run1 Run2 Run3 Run4 Run5 Run6 Run7 Run8


start of ν-mode
Data collection history

(Potons-On-Target)

Total Accumulated POT for Physics

$\nu$-Mode Beam Power

$\bar{\nu}$-Mode Beam Power

Published results


POT: $7.5 \times 10^{20} \nu, 7.5 \times 10^{20} \bar{\nu}$
Published results
POT: 7.5×10^{20} ν, 7.5×10^{20} \bar{ν}

Stable beam power at 470 kW, doubling ν POT in 1 year (NEW)
This talk: 14.7×10^{20} ν, 7.6×10^{20} \bar{ν}, totaling 29% of approved

Data collection history
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Accumulated POT

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Near Detector Samples

- **ν-mode FGD1 pμ**

- **μ− CC0π**
- **μ− CC1π**
- **μ− CCNπ**

- **ν-mode FGD1 pμ**

- **μ+ 1-track**
- **μ+ N-track**

- **μ− 1-track**
- **μ− N-track**

**Data**
- 6 ν-mode samples (FGD1,2)
- 8 ν-mode samples (FGD1,2)

**Model**
- Flux prediction: beamline MC tuned with ext. data (NA61) + beam monitor, INGRID
- Cross-section models tuned to ext. measurements.
Near Detector Fit – *post-fit*

- Data
  - 6 ν-mode samples (FGD1,2)
  - 8 ν̄-mode samples (FGD1,2)
- Simultaneous fit of $p_\mu$, $\theta_\mu$
  - Data well reproduced: p-value 0.47
  - Fitted flux parameters near nominal, most within 1σ prior uncertainty
  - Nucleon correlations (NEW): 2p2h, RPA effects significantly adjusted
  - flux $\times$ cross section at SK sys. error 13% → 3 %.
Event distributions and oscillation fit

CCQE-like sample

- 240 $\nu_\mu$
- 74 $\nu_e$
- 15 $\nu_e$

CC1$\pi^+$ sample

- 68 $\bar{\nu}_\mu$
- 7 $\bar{\nu}_e$

Reconstructed neutrino energy distributions at Super-Kamiokande

- Dotted: data; histogram: oscillation fit results, p-value 0.42

(No CC1$\pi^-$ sample due to $\pi^-$ absorption)
Event distributions and oscillation fit

CCQE-like sample

240 $\nu_\mu$

$\nu_\mu$ rate lower than fit, consistent with uncertainties.

CC1$\pi^+$ sample

74 $\nu_e$

15 $\nu_e$

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- $\nu_e$ CC1$\pi^+$ via $\Delta$ production
- $\nu_e$ W
- $\nu_e$ N
- $\nu_e$ $\Delta$

- CC1$\pi$ $\nu_e$ rate: 15 events observed vs. 6.92 maximum prediction
- P-value 0.12 for upward or downward fluctuation in at least 1 of 5 samples
Atmospheric parameter constraints

- Fit normal and inverted hierarchies separately
- Final systematics pending, possible additional contribution from interaction models (no significant impact on $\delta_{\text{CP}}$)
Appearance parameter constraints

- **Left**: T2K best-fit result and confidence intervals compared to PDG 2016: consistent
  - ν data bring in $\delta_{\text{CP}}$-sensitivity
- **Right**: T2K results with reactor constraint (PDG 2016), contour range much reduced.
Measurement of $\delta_{\text{CP}}$

- Excess in neutrino (top)
- Deficit in antineutrino (bottom)

CCQE-like $\nu_e$ and $\bar{\nu}_e$ rate compared to $\delta_{\text{CP}} = 0$ predictions:
Measurement of $\delta_{CP}$

Percentage errors on predicted event rate ratio between $\nu_e$ and $\bar{\nu}_e$ samples: relevant for $\delta_{CP}$ extraction

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ND280 constraint on flux & cross section, reducing error from 13% to 3%.
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# Measurement of $\delta_{CP}$

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Neutral current (NC) interactions not constrained by ND280. Theoretical models constrained by external measurements.
Measurement of $\delta_{CP}$

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Neutral current (NC) interactions not constrained by ND280. Theoretical models constrained by external measurements.

Total error 4.85% on event rate ratio $\nu_e / \bar{\nu}_e$ (10% by design).
Measurement of $\delta_{CP}$

Best fit point: -1.83 radians in Normal Hierarchy

$2\sigma$ CL interval:
- Normal Hierarchy: [-2.98, -0.60] radians
- Inverted Hierarchy: [-1.54, -1.19] radians

CP conserving values 0, $\pi$ both fall outside $2\sigma$ CL intervals
T2K-II Protons-On-Target Request

- Extension of T2K run to $2\times10^{21}$ POT (~2026)
- Currently approved for $7.8\times10^{21}$ POT (~2021)
- Accelerator and beam-line upgrades to 1.3 MW

3-$\sigma$ sensitivity for CP violation for favorable parameters, if
- Full T2K-II exposure $2\times10^{21}$ POT
- 50% improvement in effective statistics: horn current, SK event reconstruction
- Systematic uncertainties down to 2/3 of current size: ND upgrade
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Summary

• **NEW** since 2016 summer:
  – Doubled neutrino-mode statistics
  – New reconstruction and event selection at SK: effective improvement in statistics by ~30%
  – Improvements to neutrino interaction model

• Updated oscillation parameter estimates
  – CP conserving values of $\delta_{CP}$ are disfavored at 2σ level.

• T2K upgrade to collect $20 \times 10^{21}$ POT and achieve 3σ (in case of favorable true values of $\delta_{CP}$) sensitivity to exclude CP conserving values.
谢谢！
BACKUP
Neutrino Oscillations

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CP-odd term in appearance channels allow extraction of $\delta_{CP}$ using neutrino and anti-neutrino beams, up to $\pm 30\%$ effect at T2K – unique opportunities for experiments with accelerator neutrinos

* neglecting matter effects
Off-axis neutrino beams:
Reduce dependence on pion energy → narrow-band

Spectrum peak at maximum disappearance @SK
T2K off-axis near detector (ND280)

**P0D: Pi0 Detector**
- contains H₂O targets

**Tracker:**
- **FGD: Fine-Grained Detector**
  1. plastic scintillator C₈H₈ target
  2. C₈H₈ + H₂O target
- **Time Projection Chamber (TPC)**

**Electromagnetic Calorimeter (ECAL):**
- surrounding P0D and tracker

**Side Muon Range Detector:**
- in magnet yokes
  - constrain beam flux and cross section for oscillation analysis
  - stand-alone neutrino interaction measurements
Impact of data-driven variation on sensitivity:

\[ \text{variation} = \text{pre-fit/model prediction difference at ND280} \]

Effect seen on \( \sin^2\theta_{23} \) and \( \Delta m^2_{32} \)

Will be addressed in future by 4\( \pi \) sample, hadronic recoil, ND upgrade

Shift \( \Delta \chi^2 \) observed in data (bottom plot) by difference observed in systematic study (top plot)

Maximum change to the NH 2\( \sigma \) confidence interval was 2.3%
END