Recent T2K results on CP violation in the lepton sector

presented by

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On Behalf of the T2K Collaboration

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Outline

- Neutrino Oscillations
- The T2K Experiment
  - Beam
  - Near detectors
  - Far detector
- Results
  - $\theta_{23}$ and $\Delta m^2_{32}$
  - Electron anti-neutrino appearance
  - $\delta_{\text{CP}}$ and mass hierarchy
- Future Plans
- Conclusions
Three flavour mixing in lepton sector

The neutrino flavour eigenstates are mixtures of the mass eigenstates

Pontecorvo-Maki-Nakagawa-Sakata Mixing Matrix

Weak eigenstates

\[
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
\end{pmatrix}
= U_{\text{PMNS}}
\begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
\]

mass eigenstates

\[
U_{\text{PMNS}} = \begin{pmatrix}
1 & 0 & 0 \\
0 & +c_{23} & +s_{23} \\
0 & -s_{23} & +c_{23}
\end{pmatrix}
\begin{pmatrix}
+ c_{13} & 0 & + s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & + c_{13}
\end{pmatrix}
\begin{pmatrix}
+ c_{12} & + s_{12} & 0 \\
-s_{12} & + c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\(c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}\)

\(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \Delta m_{21}^2, \Delta m_{32}^2, \Delta m_{31}^2\)

\(*\Delta m_{ij}^2 = m_i^2 - m_j^2\)

Out of three \(\Delta m^2\)'s, number of free parameters is two. \((\Delta m_{31}^2 = \Delta m_{21}^2 + \Delta m_{32}^2)\)
Neutrino Oscillations

- Neutrino oscillations discovered in 1998
  - Neutrinos have non-zero mass and mixing angles

- Many open questions:
  - What is the neutrino mass hierarchy?
    - Is $\Delta m_{31}^2$ positive or negative?
  - Is there CP violation in the lepton sector?
    - CP symmetry is violated if $\delta_{CP} \neq 0, \pi$
  - Is the $\theta_{23}$ mixing angle maximal?
    - If not, which quadrant?
  - What are the precise values of the mixing angles $\theta_{ij}$?
  - Majorana or Dirac?

PDG2015

$$\Delta m^2_{21} = (7.53 \pm 0.2) \times 10^{-5} \text{eV}^2$$
$$\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3} \text{eV}^2$$
$$\sin^2 \theta_{12} = 0.304 \pm 0.01 \ (\theta_{12} \sim 33^\circ)$$
$$\sin^2 \theta_{23} = 0.514 \pm 0.06 \ (\theta_{23} \sim 45^\circ)$$
$$\sin^2 2\theta_{13} = 0.085 \pm 0.005 \ (\theta_{13} \sim 8^\circ)$$

normal hierarchy (NH)

$$\nu_3$$

$\Delta m^2_{23}$

$\nu_2$

$\Delta m^2_{12}$

$\nu_1$

$\nu_e \quad \nu_\mu \quad \nu_\tau$

inverted hierarchy (IH)

$$\nu_3$$

$\Delta m^2_{12}$

$\nu_2$

$\Delta m^2_{23}$

$\nu_1$

$\nu_e \quad \nu_\mu \quad \nu_\tau$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$
Neutrino oscillation probabilities at T2K

Muon neutrino survival probability:

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

\[ \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E_\nu} \right) \]

Sensitive to \( \theta_{23} \) and \( \Delta m_{32}^2 \)

Electron neutrino appearance probability (expansion by \( \alpha = \Delta m_{21}^2 / \Delta m_{31}^2 \)):

\[ P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \times \frac{\sin(\Delta \sin[x\Delta]/x)}{x} \times \cos \Delta \frac{\sin[(1-x)\Delta]}{(1-x)} \]

\[ x \equiv 2\sqrt{2}G_F N_e \frac{E_\nu}{\Delta m_{31}^2} \quad \Delta \equiv \frac{\Delta m_{31}^2 L}{4E_\nu} \]

For anti-neutrinos, replace \( \delta \) and \( x \) with -\( \delta \) and -\( x \)

- Leading term depends on \( \theta_{13} \) and \( \theta_{23} \).
- CP-violating phase \( \delta \Rightarrow P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \).
- Matter effect gives sensitivity to mass hierarchy: sign of \( x \).
Effect of CP violation at T2K

- Asymmetric effect:
  - $\delta_{\text{CP}} = -\pi/2 \rightarrow$ maximizes $P(\nu_\mu \rightarrow \nu_\epsilon)$, minimizes $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\epsilon)$
  - $\delta_{\text{CP}} = +\pi/2 \rightarrow$ minimizes $P(\nu_\mu \rightarrow \nu_\epsilon)$, maximizes $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\epsilon)$
- Effect of $\delta_{\text{CP}}$ and Mass Hierarchy on appearance probability is similar. Size of effect:
  - $\delta_{\text{CP}}$: 0 to (±) 20% effect
  - Mass hierarchy: ±10%
The T2K collaboration includes about 500 members from 11 countries (Canada, France, Germany, Italy, Japan, Poland, Russia, Spain, Switzerland, UK, USA).
The T2K Experiment

Off-axis $\nu^\mu$ beam 2.5°
Neutrino flux peaks at 0.6 GeV
Less than 1% $\nu_e$ under the peak

Two production modes:
Neutrino and anti-neutrino

Super Kamiokande

Near Detector

J-PARC

Mt. Noguchi-Goro
2924 m

Mt. Ikeno-Yama
1360 m

SK: 50 kt water, 22.5 kt fiducial

INGRID

ND280

In Japan

280 m

Water equiv.

1700 m

295 km

Neutrino beam
Bird’s eye view of J-PARC

Main Ring

Near Detector

To Kamioka

Neutrino

Linac

Rapid Cycling Synchrotron
30 GeV proton beam from J-PARC main ring
90 cm graphite target
Neutrinos produced from pion and kaon decays
  For anti-neutrinos: Invert focusing-horn polarity which selects the charged pions and kaons
  Dedicated hadron production measurements from NA61/SHINE crucial for T2K (anti)neutrino flux predictions
Off-axis beam: centre of beam direction 2.5° off from direction to SK
  Narrow beam energy peak around oscillation maximum,
  Fewer high-energy neutrinos, so less problematic background
Near Detectors: INGRID

- On-axis detector,
- Consists of 16 modules, 7 horizontal, 7 vertical and 2 off diagonal, each module is a cube of 1 m$^3$,
- Each module is a sandwich of 11 scintillator and 10 iron layers, surrounded by 4 veto planes,
- Neutrino beam centre is obtained with accuracy of ~ 0.1 mrad from horizontal/vertical distribution of neutrino event rate,

Provides cross section measurements and constraining beam flux
Near Detectors: ND280

- Off-axis detector
- 2 Fine-Grained Detectors (FGDs) of scintillator bars, one has water target,
- 3 gas-filled TPCs to reconstruct and identify charged particle tracks
- 0.2 T magnetic field used for charged particle momentum determination
- Information on neutrino flux and interactions from reconstructed tracks

ND280 strongly reduces systematic uncertainties of T2K oscillation analysis
Far Detector: Super Kamiokande

- Situated 1000 m under ground in Kamioka mine, 295 km from J-PARC
- 50 kt water Cherenkov detector with a fiducial volume of 22.5 kt
- Inner Detector is instrumented with 11129 20-inch PMTs
- Outer Detector has 1885 8-inch PMTs
Particle ID and Event Selection

- Select 1 ring events for analysis

**ν_μ selection**
- μ-like PID
- p_μ > 200 MeV/c
- At most 1 Michel electron

**ν_e selection**
- e-like PID
- p_e > 100 MeV/c
- No Michel electron
- E_{rec} < 1.25 GeV
- Pass π^0 rejection

MC \( ν_μ → μ \)

Sharp Cherenkov ring, only direct light from μ

MC \( ν_e → e \)

Fuzzier Cherenkov ring, due to scatter/EM shower

Excellent μ/e separation

Probability to misidentify a muon as an electron < 1%
Data Sample

Results with full good quality data up to May 27:

- $\nu$-mode: $7.48 \times 10^{20}$ POT
- $\bar{\nu}$-mode: $7.47 \times 10^{20}$ POT

- Accumulated almost the same number of POT in $\nu$- and $\bar{\nu}$-mode
Analysis Method

\[ N_{ND} \sim (\sigma \Phi)_{ND} \epsilon_{ND} \]

\[ N_{SK} \sim (\sigma \Phi)_{SK} \epsilon_{SK} \]

\[ \Delta N_{SK}/N_{SK} \sim 5\% \]

\[ \theta_{13}, \theta_{23}, \Delta m^2_{31/32}, \delta_{CP} \] (\( \theta_{12} \) and \( \Delta m^2_{21} \) fixed from other experiments)
Systematic Uncertainties

- Expected events at SK as a function of reconstructed neutrino energy
- ND280 reduces the systematic uncertainties on expected neutrino events at SK from 12-14% to 5-6%
Results

The results presented in this talk are from the analysis of the combined T2K neutrino and antineutrino data samples \((\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e)\) with four parameters \((\delta_{CP}, \theta_{13}, \theta_{23}, \Delta m^2_{32})\) fitted simultaneously.
ν and ¯ν disappearance

Disappearance and distortion of energy spectrum for both ν and ¯ν

Previous publications: PRL 112 181801 (2014)
PRD 91 07210 (2015)
PRL 116, 181801(2016)

ν and ¯ν results are consistent

No evidence of CPT violation
Constraints on $\theta_{23}$ and $\Delta m^2_{32}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal Hierarchy</th>
<th>Inverted Hierarchy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Best fit  $\pm 1\sigma$</td>
<td>Best fit  $\pm 1\sigma$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.532 [0.464; 0.578]</td>
<td>0.534 [0.468; 0.577]</td>
</tr>
<tr>
<td>$\Delta m^2_{32} (10^{-3} \text{eV}^2)$</td>
<td>2.545 [2.461; 2.626]</td>
<td>2.510 [2.427; 2.591]</td>
</tr>
</tbody>
</table>
Neutrino mode

T2K Run 1-7c preliminary

Unoscillated Prediction
Best-Fit
Data

Events
Ratio
Reconstructed Momentum [MeV/c]

Anti-neutrino mode

T2K Run 1-7c preliminary

Unoscillated Prediction
Best-Fit
Data

Events
Ratio
Reconstructed Momentum [MeV/c]

<table>
<thead>
<tr>
<th>Beam mode</th>
<th>Sample</th>
<th>Exp. Not Osc</th>
<th>Exp. $\delta_{CP} = 0$ (NH)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrino</td>
<td>e-like</td>
<td>6.1</td>
<td>24.2</td>
<td>32</td>
</tr>
<tr>
<td>antineutrino</td>
<td>e-like</td>
<td>2.3</td>
<td>6.9</td>
<td>4</td>
</tr>
</tbody>
</table>

Clear appearance signal for $\nu_e$
More statistics needed for $\bar{\nu}_e$

Previous publications: PRL 112, 061802(2014)
PRD 91, 072010(2015)
Constraints on $\theta_{13}$ and $\delta_{CP}$

Number of $\nu_e$ and $\bar{\nu}_e$ candidates compared with predictions:

- Number of observed events shows larger asymmetry than expected for $\delta_{CP} = -\pi/2$ and NH

T2K-only data fit

Reactor experiment constraint from PDG 2015 ($\sin^2 2\theta_{13} = 0.085 \pm 0.005$) shown

- $\theta_{13}$ in agreement with reactor experiments
- T2K begins to probe $\delta_{CP}$
  - $\delta_{CP} \sim -\pi/2$ and NH preferred
- T2K disfavors region of $\delta_{CP} = +\pi/2$
Constraints on $\delta_{CP}$

90% CL constraints on $\delta_{CP}$ from Feldman-Cousins method

Reactor constraint:
$\sin^2 2\theta_{13} = 0.085 \pm 0.005$ (PDG 2015)

- Best fit gives $\delta_{CP} = -1.791$, Normal Hierarchy
- The allowed 90% CL intervals are:
  - $-3.13 < \delta_{CP} < -0.39$ (NH)
  - $-2.09 < \delta_{CP} < -0.74$ (IH)
- CP conserving values $\delta_{CP} = 0$ and $\pi$ are excluded at 90% C.L.

CP conservation hypothesis excluded at 90% CL
Future Plans
T2K-II

- T2K: ends when $7.8 \times 10^{21}$ POT is reached (expected around 2021)
- T2K-II: proposed extension up to 2026 for $20 \times 10^{21}$ POT
  - Stage 1 status at this summer's J-PARC PAC (Program Advisory Committee)
- Plan to gradually increase the beam intensity (currently ~ 400 kW) up to 1 MW in 2021
- J-PARC accelerator and beam-line upgrade:
  - Beam power up to 1.3 MW in ~2026
- Upgrade of near detectors to improve systematic uncertainties
- Possible increase of SK fiducial volume

A step towards Hyper-Kamiokande

[arXiv: 1609.04111]
**Physics Potential of T2K-II**

**Unknown Mass Hierarchy**

**Mass Hierarchy Known**

Sensitivity for $\sin^2\theta_{23} = 0.43$

With full T2K-II statistics able to:

- Exclude CP conservation hypothesis at more than 3σ if $\delta_{CP} \sim -\pi/2$
- Measure $\theta_{23}$ with resolution $\sim 1.7^\circ$
Conclusions

- Since 2010 T2K has accumulated \( \sim 1.5 \times 10^{21} \) POT, 19% of expected total, split equally in neutrino and anti-neutrino mode

- First search for CP violation in the lepton sector with analysis using both neutrino and anti-neutrino data (\( \nu_\mu / \bar{\nu}_\mu \) disappearance, \( \nu_e / \bar{\nu}_e \) appearance)
  - Leading results for \( \theta_{23} \) and \( \Delta m^2_{32} \)
    - Data prefer maximal (\( \theta_{23} = 45^\circ \)) \( \nu_\mu / \bar{\nu}_\mu \) disappearance
  - CP conservation hypothesis excluded at 90% CL
    - \( \delta_{CP} = [-3.13,-0.39] \) NH, \([-2.09,-0.74]\) IH

- Expect to double neutrino data by summer 2017 and to reach \( 7.8 \times 10^{21} \) POT around 2021

- Proposed extension to T2K:
  - Accumulate \( 20 \times 10^{21} \) POT by 2026,
  - Reach > 3\( \sigma \) sensitivity to \( \delta_{CP} \sim -\pi/2 \)
BACKUP
Flux Prediction

- Neutrino and anti-neutrino flux prediction tuned with hadron spectra from NA61/SHINE
- Flux uncertainty reduced from ~30% to ~10% (thin target data)

- Less than 1% electron (anti)neutrino component at the peak,
- <10% wrong-sign background,
- Using predictions of flux correlations between near/far, neutrino/anti-neutrino beam $\nu_\mu / \nu_e$
NA61/SHINE experiment at CERN SPS

- Large-acceptance detector with very good capabilities of charge and mass measurements
- Located in the CERN North Area
- Cover almost full T2K \{p,\Theta\} phase space
- Measure pion, proton and kaon production with 31 GeV/c proton beam on carbon target
  - Thin 2cm target (Eur. Phys. J. C 76, 84 (2016))
  - T2K replica target (published $\pi^\pm$ yields: Eur. Phys. J. C 76, 617 (2016))
### Systematics

<table>
<thead>
<tr>
<th>Beam mode</th>
<th>sample</th>
<th>$\delta N_{SK}/N_{SK}$ w/o ND280</th>
<th>ND280</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrino</td>
<td>$\mu$-like</td>
<td>12.0%</td>
<td>5.0%</td>
</tr>
<tr>
<td>neutrino</td>
<td>e-like</td>
<td>11.9%</td>
<td>5.4%</td>
</tr>
<tr>
<td>antineutrino</td>
<td>$\mu$-like</td>
<td>12.5%</td>
<td>5.2%</td>
</tr>
<tr>
<td>antineutrino</td>
<td>e-like</td>
<td>13.7%</td>
<td>6.2%</td>
</tr>
</tbody>
</table>

- Improvements given by measurements with ND280 data
Near detector neutrino sample for systematics constraint

Neutrino samples, best-fit distributions

1 $\mu^-$ candidates
Near detector anti-neutrino sample for systematics constraint

Anti-neutrino samples, best-fit distributions

1 $\mu^+$ candidates
SK $\nu / \bar{\nu}$ selection

1) Fully contained in fiducial volume rings
2) $\mu$-like PID
3) Single ring event
4) Momentum $> 200$ MeV
5) # decay electron $\leq 1$

No magnetic field: same selection for neutrino and anti-neutrino beam
SK $\nu_e/\bar{\nu}_e$ selection

1) Fully contained in fiducial volume rings
2) e-like PID
3) Single ring event
4) $E_{\text{visible}} > 100$ MeV

5) # decay $e^- = 0$
6) $0 < E_{\text{rec}} < 1250$ MeV
7) $\pi^0$ rejection cut

No magnetic field: same selection for neutrino and anti-neutrino beam

18/12/16 Miami 2016
SK spectra

- Predicted spectra at SK compared to candidate events
- Energy reconstructed assuming 2-body kinematics