INITIAL PROBE OF $\delta_{CP}$ BY THE T2K EXPERIMENT

Lorena Escudero
for the T2K Collaboration
July 3rd, 2014 - Valencia, Spain
Neutrinos and CP Violation

Long-baseline neutrino experiments which have access to 3-flavour neutrino oscillations, like T2K, can search for CP violation in the lepton sector by measuring the $\delta_{CP}$ phase.

\[
U_{PMNS} = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\alpha_1} & 0 \\
0 & 0 & e^{i\alpha_2}
\end{pmatrix}
\]

Atmospheric  Interference  Solar  Majorana phases

$\sin(\theta_{ij}) = s_{ij}$  $\cos(\theta_{ij}) = c_{ij}$  $\delta = \delta_{CP}$

**CP violation** is one of the key ingredients of leptogenesis: its observation in the lepton sector, together with L violation, could connect leptogenesis and the origin of the baryon asymmetry!
Neutrino Oscillations at T2K

T2K is optimized for two kind of neutrino oscillation analyses: **ν_μ disappearance** and **ν_e appearance**

**ν_μ disappearance** \((\sin^2\theta_{23}, \Delta m^2_{32})\)

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

**ν_e appearance** \((\sin^2\theta_{13}, \delta_{CP})\)

\[
P(\nu_\mu \rightarrow \nu_e) \approx \\
\sin^2 \theta_{23} \sin^2 \theta_{13} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E_\nu} \right) \sin^2 \left( \frac{\Delta m^2_{32} L}{4E_\nu} \right) \sin^2 \left( \frac{\Delta m^2_{21} L}{4E_\nu} \right) \sin \delta_{CP} \\
- \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin^2 \left( \frac{\Delta m^2_{32} L}{4E_\nu} \right) \sin^2 \left( \frac{\Delta m^2_{31} L}{4E_\nu} \right) \sin^2 \left( \frac{\Delta m^2_{21} L}{4E_\nu} \right) \sin \delta_{CP} \\
+ CPC + matter + solar terms
\]

In addition, T2K has recently performed its first **joint oscillation analysis** combining both neutrino oscillation channels.

---

Lorena Escudero, ICHEP 2014
The Tokai to Kamioka Experiment

T2K is the first long-baseline neutrino oscillation experiment with an off-axis configuration.

Uses a highly pure muon neutrino beam: generated at J-PARC accelerator, characterized by near detectors and directed towards Super-Kamiokande (SK) far detector.

Near Detectors (Tokai, 280m from target)

CURRENT DATASET

From January 2010 to May 2013 (Run1+2+3+4)
Accumulated $6.57 \times 10^{20}$ POT (~8% of final design goal POT)
T2K Event Selection at SK

1. Fully Contained Fiducial Volume
2. SINGLE RING
3. PID

377 FCFV events
T2K Event Selection at SK

- Fully Contained Fiducial Volume
- SINGLE RING
- PID

377 FCFV events

- μ-like clear ring
T2K Event Selection at SK

- Fully Contained Fiducial Volume
- SINGLE RING
- PID

377 FCFV events

- $p_\mu > 200$ MeV/c
- Decay $e^- < 2$

μ-like
- clear ring

$120 \nu_\mu$ events

Lorena Escudero, ICHEP 2014
T2K Event Selection at SK

1. Fully Contained Fiducial Volume
2. SINGLE RING
3. PID

- **e-like**
  - 377 FCFV events
  - fuzzy ring

- **μ-like**
  - $p_\mu > 200$ MeV/c
  - clear ring

- Decay $e^- < 2$

- **120 $\nu_\mu$ events**

Lorena Escudero, ICHEP 2014
T2K Event Selection at SK

Fully Contained Fiducial Volume → SINGLE RING → PID

- **e-like**
  - 377 FCFV events
  - Decay $e^- = 0$
  - $E_{vis} > 100\text{MeV/c}$
  - $E_{rec} < 1250\text{MeV}$
  - $\pi^0$ rejection
  - $28 \nu_e$ events

- **μ-like**
  - Decay $e^- < 2$
  - $p_\mu > 200\ \text{MeV/c}$
  - $120 \nu_\mu$ events

- **fuzzy ring**

- **clear ring**

Lorena Escudero, ICHEP 2014
Relative Uncertainty (%) in the Expected Number of Events*

<table>
<thead>
<tr>
<th>$\nu_e$</th>
<th>SYSTEMATIC SOURCE</th>
<th>$\nu_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Flux &amp; Correlated Cross Sections</td>
<td>2.7</td>
</tr>
<tr>
<td>4.7</td>
<td>Independent Cross Sections</td>
<td>5.0</td>
</tr>
<tr>
<td>2.4</td>
<td>$\pi$ Hadronic Interactions (FSI)</td>
<td>3.0</td>
</tr>
<tr>
<td>2.7</td>
<td>SK Detector Efficiencies</td>
<td>4.0</td>
</tr>
<tr>
<td>6.8</td>
<td>TOTAL</td>
<td>7.6</td>
</tr>
</tbody>
</table>

*At the neutrino oscillation parameters: $\sin^22\theta_{13} = 0.1$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$/c$^4$, $\delta_{CP} = 0$, NH
T2K Observation of $\nu_e$ Appearance

$\nu_e$ appearance in a $\nu_\mu$ beam with 7.3 $\sigma$ significance

The latest T2K appearance analysis was performed with $6.57 \times 10^{20}$ POT (~8% goal POT) and it has shown the strongest evidence of $\nu_e$ appearance in a $\nu_\mu$ beam.

Maximum likelihood fit in $(p_e, \theta_e)$

Fixing $\theta_{23}$ and $\Delta m^2_{32}$

NOTE: 1D contours for various values of $\delta_{CP}$

Adding Reactor Constraint

**NOTE:** 1D contours for various values of $\delta_{CP}$

$\sin^2 2\theta_{13} = 0.136^{+0.044}_{-0.033}$

$\Delta m^2_{32} > 0$

$\Delta m^2_{32} < 0$

**REACTOR MEASUREMENT**

Marginalizing over $\theta_{23}$ and $\Delta m^2_{32}$

$\sin^2 2\theta_{13} = 0.166^{+0.051}_{-0.042}$

$\sin^2 2\theta_{13} = 0.136^{+0.044}_{-0.033}$

$\sin^2 2\theta_{13} = 0.166^{+0.051}_{-0.042}$

**Best-fit value obtained for $\sin^2 2\theta_{13}$ is larger than the reactor value**

When applying the reactor constraint, region where $\sin^2 2\theta_{13}$ is as small as possible is favored

Due to $\delta_{CP}$ - $\sin^2 2\theta_{13}$ correlation, this favored region is for $\delta_{CP} \approx -\pi/2$ (lucky point!)

**and the first hint toward $\delta_{CP} \approx -\pi/2$**


$\sin^2 \theta_{23}, \Delta m^2_{32}$ were marginalized following the $\Delta \chi^2$ surface from the previous T2K $\nu_\mu$ disappearance analysis with $3.01 \times 10^{20}$ POT (Run 1+2+3)

![Physics](https://example.com/physics)

**Viewpoint: Neutrino Experiments Come Closer to Seeing CP Violation**

Joseph A. Formaggio, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

Published February 10, 2014, | Physics 7, 15 (2014) | DOI: 10.1103/Physics.7.15

![AGS Journals](https://example.com/ags-journals)

**Physics**

Lighting exceptional research

Lorena Escudero, ICHEP 2014
Motivation for Joint Oscillation Analysis

• The stand-alone analyses assume priors for the oscillation parameters not directly studied.
• Dependency between oscillation parameters, clear in the 3-flavour probabilities:

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \cdot \sin^2 \left( 1.27 \Delta m^2_{13} \frac{L}{E} \right) \]

Next step to take all the dependencies into account is to perform a \textit{joint oscillation analysis}.
T2K Joint $\nu_\mu + \nu_e$ Oscillation Analysis

The four neutrino oscillation parameters are fitted at the same time without priors

Two approaches

Frequentist: CONFIDENCE REGIONS using a likelihood ratio fit

Bayesian: CREDIBLE INTERVALS using Markov Chain Monte Carlo (MCMC)
**T2K Joint $\nu_\mu + \nu_e$ Frequentist Analysis**

**FREQUENTIST:** likelihood ratio fit of $\nu_\mu + \nu_e E_{\text{rec}}$ spectra

Combining T2K joint analysis with reactor constraint (PDG 2013):

$\sin^2 2\theta_{13} = 0.095 \pm 0.01$

$\sin^2 \theta_{23}, \Delta m_{32}^2$ and $\sin^2 2\theta_{13}$ are marginalized following the 3D $\Delta \chi^2$ surface from Run1+2+3+4

<table>
<thead>
<tr>
<th>$\delta_{CP}$ EXCLUDED REGIONS</th>
<th>BEST FIT</th>
<th>90% CL ($\pi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH</td>
<td>-0.495</td>
<td>[0.146, 0.825]</td>
</tr>
<tr>
<td>IH</td>
<td>-0.495</td>
<td>[-0.080, 1.091]</td>
</tr>
</tbody>
</table>

Don’t miss my poster!!

Lorena Escudero, ICHEP 2014
**T2K Joint $\nu_\mu + \nu_e$ Bayesian Analysis**

**BAYESIAN:**
Markov Chain Monte Carlo (MCMC) with both ND280 and SK $\nu_\mu + \nu_e$ samples

Combining T2K joint analysis with reactor constraint (PDG 2013):
$\sin^2 2\theta_{13} = 0.095 \pm 0.01$

Marginalized over mass hierarchy

Assuming flat priors for $\sin^2 \theta_{23}$, $|\Delta m_{32}^2|$; $P(NH) = P(IH) = 0.5$

90% CI Inclusion:
$\delta_{CP} \in [-1.13, 0.14]\pi$

### POSTERIOR PROBABILITIES

<table>
<thead>
<tr>
<th></th>
<th>NH</th>
<th>IH</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23} \leq 0.5$</td>
<td>18%</td>
<td>8%</td>
<td>26%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23} &gt; 0.5$</td>
<td>50%</td>
<td>24%</td>
<td>74%</td>
</tr>
<tr>
<td><strong>SUM</strong></td>
<td>68%</td>
<td>32%</td>
<td></td>
</tr>
</tbody>
</table>
T2K Antineutrino Running

**NEXT STEP: COMBINING NEUTRINO AND ANTINEUTRINO DATA**

**FIRST SHORT T2K ANTINEUTRINO RUN IN JUNE 2014**

First anti-$\nu_\mu$ induced CCQE event candidate at the T2K near detector ND280 with anti-$\nu_\mu$ beam setting

First FCFV event at SK with anti-$\nu_\mu$ beam setting
Future Sensitivity to $\delta_{CP}$

SENSITIVITY STUDIES (at goal $7.8 \times 10^{21}$ POT)
TO RESOLVE $\sin(\delta_{CP}) \neq 0$

**T2K DATA ONLY**

Using joint oscillation analysis assuming 50% $\nu$ and 50% anti-$\nu$ running with realistic 2012 systematic errors ($\sim 10% \nu_{e} \sim 13% \nu_{\mu}$)

Studies indicate that T2K best sensitivity will be for 50% $\nu$ and 50% anti-$\nu$ running

**T2K+NOvA**

Using GLoBES, assuming 50% $\nu$ and 50% anti-$\nu$ running for both experiments, and 5% (10%) normalization uncertainty on signal (background) for dashed lines (no syst solid lines)

NOTE: With projected reactor constraint $\sin^{2}2\theta_{13}=0.1\pm0.005$
Conclusions

With only \( \sim 8\% \) of its final design goal POT, T2K has observed \( \nu_e \) appearance in a \( \nu_\mu \) beam with 7.3\( \sigma \) significance and has shown hints toward \( \delta_{CP} \approx -\pi/2 \) combined with reactor constraint:

- First hint with \( \nu_e \) appearance analysis (reactor values from PDG2012)
- Updated with joint oscillation analysis and reactor values from PDG2013
  - Larger excluded regions (preliminary)
  - New bayesian treatment

\[ \text{T2K sensitivity studies to resolve } \sin(\delta_{CP}) \neq 0 \text{ show that:} \]
- Some regions for \( \delta_{CP} \) can be resolved at 90\% CL depending on \( \sin^2 \theta_{23} \)
- Enhanced sensitivity combining T2K and NOvA

**MORE DATA AND ANTI-NEUTRINO DATA COMING... STAY TUNED TO T2K!**

---

Feldman-Cousins 90\% CL inclusion regions for \( \delta_{CP} \):

\[
\begin{align*}
\text{NH} : & [-1.175, 0.146]^{\pi} \\
\text{IH} : & [-0.909, -0.080]^{\pi}
\end{align*}
\]

Bayesian 90\% CI inclusion region for \( \delta_{CP} \):

\[
\begin{align*}
\text{NH} : & [-1.13, 0.14]^{\pi} \\
\text{IH} : & [-0.909, -0.080]^{\pi}
\end{align*}
\] (marginalized over MH)

\( \delta_{CP} \approx -\pi/2 \) further preferred with latest reactor results (Neutrino2014)