RECENT OSCILLATION RESULTS FROM THE T2K EXPERIMENT

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on behalf of the T2K collaboration

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OUTLINE

- Introduction
  - Neutrino oscillation phenomenology
- T2K experiment
- Oscillation results
- Summary + further plans
Neutrino Oscillations

- Neutrino born/interacts in flavor eigenstates, while travelling is described in mass eigenstates $\rightarrow$ neutrino can change flavor while travelling in vacuum/matter

- PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix parameterizes mass-flavor mixing:

$$
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
\end{pmatrix} =
\begin{pmatrix}
    1 & 0 & 0 \\
    0 & c_{23} & s_{23} \\
    0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
    c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\
    0 & 1 & 0 \\
    -s_{13} e^{i\delta_{CP}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
    c_{12} & s_{12} & 0 \\
    -s_{12} & c_{12} & 0 \\
    0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
$$

$$
\sin^2 \theta_{23} = 0.44^{+0.03}_{-0.02}
$$

$$
|\Delta m_{32}^2| = (2.61 \pm 0.06) \cdot 10^{-3} eV^2/c^4
$$

Experimental challenges:

1. Measure osc. parameters as precisely as possible
2. CP-violation discover $\delta_{CP} \neq 0, \pi$
3. Mass ordering: (Normal Order: $m_1 < m_2 < m_3$ or Inverted Order: $m_3 < m_1 < m_2$)
4. $\theta_{23}$ octant ($< \text{or} > 45^\circ$)
5. Exotics: 4th flavor, etc.
**Oscillation Probabilities**

- **T2K studies** $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$ and anti-neutrino modes

\[
P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta_{31}
\]

Disappearance: 1. Sensitive to $\theta_{23}$

\[
\Delta_{31} = \frac{\Delta m_{31}^2 L}{4E}
\]

\[
P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta_{31}]}{(1-x)^2}
\]

\[-\alpha \sin \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin \Delta_{31} \]

\[+\alpha \cos \delta_{CP} \times \sin 2\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos \Delta_{31}
\]

Appearance: 1. Sensitive to $\delta_{CP}$
2. Sensitive to matter effect
3. Sensitive to $\theta_{23}$ octant

\[
\alpha = \frac{|\Delta m_{21}^2|}{|\Delta m_{31}^2|}
\]

**Matter effect:**
\[
x = \frac{2\sqrt{2}G_FN_eE}{\Delta m_{31}^2}
\]

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T2K oscillation results

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Produce neutrino mainly in pion decays:

\[ \nu\text{-mode} \quad \pi^+ \rightarrow \nu_\mu + \mu^+ \]
\[ \bar{\nu}\text{-mode} \quad \pi^- \rightarrow \bar{\nu}_\mu + \mu^- \]

Off-axis concept:

\[
\frac{dE_\nu}{dE_\pi} = \left(1 - \frac{m_\mu^2}{m_\pi^2}\right) \frac{1 - \gamma^2 \theta^2}{(1 + \gamma^2 \theta^2)^2}
\]

for \( \theta = \gamma_\pi^{-1} = m_\pi/E_\pi \)

\( E_\nu \) is monoenergetic

Tune for the 1\textsuperscript{st} oscillation maximum:

\( L = 295 \text{ km} \quad \Rightarrow \quad E_\nu \approx 0.6 \text{ GeV} \)
NEAR DETECTORS (ND280 & INGRID)

Use NA61 (CERN) measurements for meson production estimations

**Off-axis:**
- CH and water targets
- use for $\nu$ flux fitting
- use for $\nu$ cross sections fitting
- reduce systematics in osc. analysis:
  - $\mu$-like 12% $\rightarrow$ 5%
  - $e$-like 12% $\rightarrow$ 7%

**On-axis:**
- Iron target
- precise $\nu$ beam direction measurements
- $\bar{\nu}$ beam intensity

$$N_{ND} = \int \phi_{ND}(E) \times \sigma(E) \times \epsilon_{ND}(E) \times dE$$

Neutrino cross sections at T2K energies from PDG 2016
FAR DETECTOR (SUPER-KAMIOKANDE)

50-kt water Cherenkov detector
22.5 kt Fiducial Volume
11 129 + 1 885 = 13 014 PMTs
inner detector outer detector

For oscillation analysis use 5 samples:
• 1 \(\mu\)-like ring and 1 \(e\)-like ring for \(\nu\) and \(\bar{\nu}\) modes \(\rightarrow\) CCQE

• CC1\(\pi^+\) \(e\)-like ring for \(\nu_e\) \(\rightarrow\) \(e\)-like ring from Michel electron exists
• compute \(E_{\nu}\) with \(\Delta^{++}\) assumption
• \(\rightarrow\) increase statistics by 10% \(\nu_{\text{cross}}\)
\(\nu_{\text{flux}}\) section FD efficiency oscillation probability

\[N_{SK} = \int \phi_{SK}(E) \times \sigma(E) \times \epsilon_{FD}(E) \times P(\nu_{\alpha} \rightarrow \nu_{\beta}, E) \times dE\]
DATA TAKING

Total analyzed data run 1-7:

$7.482 \times 10^{20} \text{ POT } \nu, 7.471 \times 10^{20} \text{ POT } \bar{\nu}$

Total accumulated data:

$\approx 23 \times 10^{20} \text{ POT, analyzed + run 8 (} \approx 8 \times 10^{20} \text{ POT } \nu)$

POT = Protons On Target
Analysis strategy:
- joint maximum-likelihood fit of the five far detector samples
- use 3-flavor oscillation model
- take into account matter effect ($\rho = 2.6 \text{ g/cm}^3$)

Various techniques were used:
- hybrid Bayesian-frequentist approach
- fully Bayesian method
- Markov Chain Monte Carlo method

All three methods are in a good agreement
$\nu_\mu$ AND $\bar{\nu}_\mu$ DISAPPEARANCE

\begin{align*}
\nu_\mu & \quad 135 \text{ events} & \quad \bar{\nu}_\mu & \quad 66 \text{ events} \\
521.777 & \quad \text{Observed} & \quad 184.837 & \quad \text{Expect w/o oscillations}
\end{align*}
The T2K data slightly prefer the second octant $\sin^2 \theta_{23} > 0.5$ with no hints of CPT violation.

Using reactor measurement, $\sin^2 2\theta_{13} = 0.085 \pm 0.005$

**Best fit:**

- $\sin^2 \theta_{23} = 0.532$
- $|\Delta m^2_{32}| = 2.545 \times 10^{-3} \text{eV}^2 / c^4$

- $\sin^2 \theta_{23} = 0.534$
- $|\Delta m^2_{32}| = 2.510 \times 10^{-3} \text{eV}^2 / c^4$

The T2K data slightly prefer the second octant ($\sin^2 \theta_{23} > 0.5$) with no hints of CPT violation.
**$\delta_{CP}, \theta_{13}$ MEASUREMENTS**

Good agreement with reactor results

CP conservation ($\delta_{CP} = 0, \pi$) is excluded with a significance of 90% C.L.

The best-fit value of $\delta_{CP}$ is close to $-\pi/2$

$\sin^2 2\theta_{13} = 0.085 \pm 0.005$
FURTHER PLANS

- T2K is approved to take $7.8 \times 10^{21} POT$
- T2K II proposal: $20 \times 10^{21} POT$

Sensitivity to CP violation with $20 \times 10^{21} POT$ statistics and systematic 2/3 to current

Mass ordering is unknown

Mass ordering is known measured by outer experiment

T2K oscillation results

From arXiv:1607.08004
**SUMMARY**

- First joint $\nu_\mu/\bar{\nu}_\mu$ & $\nu_e/\bar{\nu}_e$ analysis
- Precise measurements of $\theta_{23}$ and $|\Delta m^2_{32}|$ were performed
  - data slightly prefer $\sin^2\theta_{23} > 0.5$
- CP conservation is excluded (90% C.L.)
  - best fit of $\delta_{CP}$ is near $-\pi/2$

**FUTURE PLANS**

- T2K is approved to take $7.8 \times 10^{21} POT$
- prospects for T2K II ($20 \times 10^{21} POT$)
  - $3\sigma$ sensitivity to CP violation
  - more accurate osc. parameters measurement
THE T2K COLLABORATION

~500 members, 63 Institutes, 11 countries

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute of Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U. of Science
Yokohama National U.

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington
The latest published result for the 4 sample analysis. Normal mass ordering using reactor measurement:

\[ \sin^2 2\theta_{13} = 0.085 \pm 0.005 \]