Neutrino Physics: The T2K Experiment

Wei-Chih Huang

National Tsing Hua University

January 11, 2019

Overview

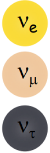
1. Physics Behind the Experiment
   - 3-Flavor Neutrino Oscillation
   - The Probability of the Oscillation
   - Physical Process
   - Detection Method
2. T2K Experiment
   - T2K Collaboration
   - Goal of The Experiment
   - Experiment Setup
   - T2K Neutrino Beamline
   - Advantage of off-axis beam
3. Results Data
   - ν_μ Disappearance
   - ν_e Appearance
   - CP Violation
   - Possible Implication

Physics Behind the Experiment

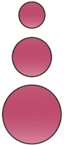
- 3-Flavor Neutrino Oscillation
- The Probability of the Oscillation
- Physical Process
- Detection Method

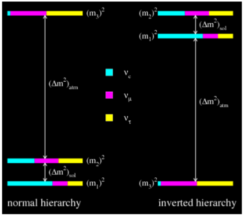
3-Flavor Neutrino Oscillation

Weak eigenstates　　　　Mass eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PNMS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \begin{matrix} m_1 \\ m_2 \\ m_3 \end{matrix}$$





$$U_{\mathrm{PNMS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{+i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$P(\nu_a \to \nu_b) = \delta_{ab} - 4\sum_{i>j} (U_{ai}U_{bi}U_{aj}U_{bj}) \sin^2\left(\Delta m^2_{ij} L/4E\right) \qquad \Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

- 6 independent parameters in 3 mixing angles, 1 complex phases, 3 mass-squared differences.
  - Mass hierarchy (sign of Δm^2_{32}) and δ_{CP} are not determined yet. ← Accelerator-based Long baseline ν oscillation experiment can address.

The Probability of the Oscillation

$$P(\nu_\mu \to \nu_\mu) \simeq 1-\left(\cos^4\theta_{13}\cdot\sin^2 2\theta_{23}+\sin^2 2\theta_{13}\cdot\sin^2\theta_{23}\right)\cdot\sin^2\left(\frac{\Delta m^2_{31}\cdot L}{4E_\nu}\right)$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}\left(1-2\sin^2\theta_{13}\right)\right)$$

$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\sin\delta_{CP}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)+\cdots$$

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1-\frac{2a}{\Delta m^2_{31}}\left(1-2\sin^2\theta_{13}\right)\right)$$

$$+\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\sin\delta_{CP}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)+\cdots$$

Physical Process

$$p + \underset{\text{first layer}}{\text{graphite}} \rightarrow \pi \xrightarrow{\text{decay}} \mu + \nu_\mu$$

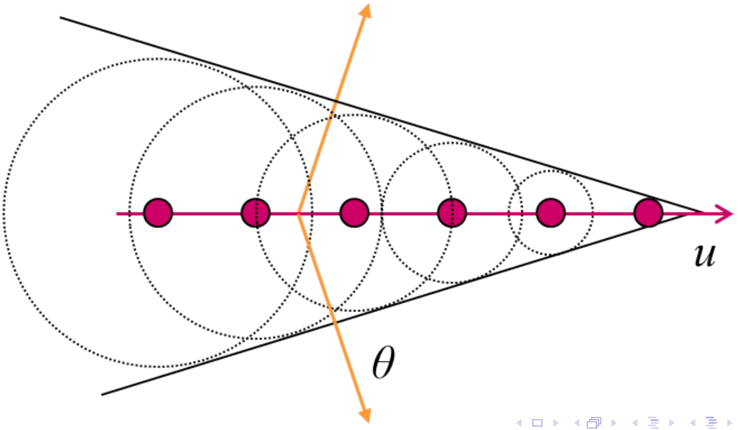
$\Rightarrow \mu$, p, π are stopped by second layer of graphite, only ν_μ pass

low/high energy neutrino oscillate in short/long distance

$600MeV \Rightarrow 295km$

Detection Method

ν_μ + ordinary matter(water) $\rightarrow \mu^-$ or e^-
$\rightarrow$ Cherenkov radiation



T2K Experiment

- T2K Collaboration
- Goal of The Experiment
- Experiment Setup
- T2K Neutrino Beamline
- Advantage of off-axis beam

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
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

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

2

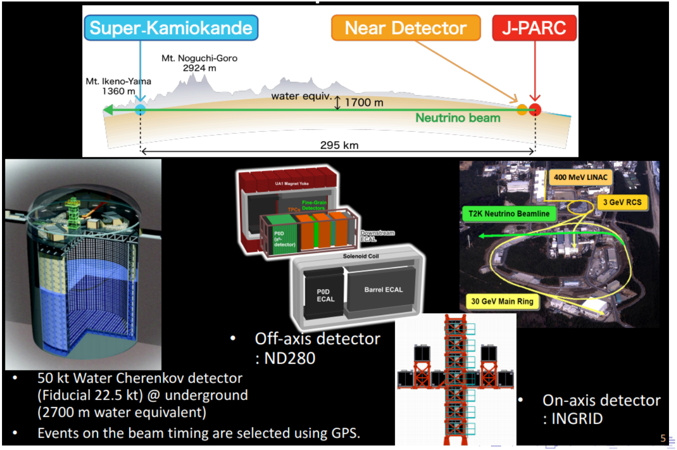
Goal of The Experiment

- Precise measurement θ_{23} of $\nu_\mu \to \nu_\mu$ disappearance
- Direct search for $\nu_\mu \to \nu_e$ oscillation (i.e., the confirmation that $\theta_{13} > 0$)
- Search for CP violation phenomena in the lepton sector - Difference between $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

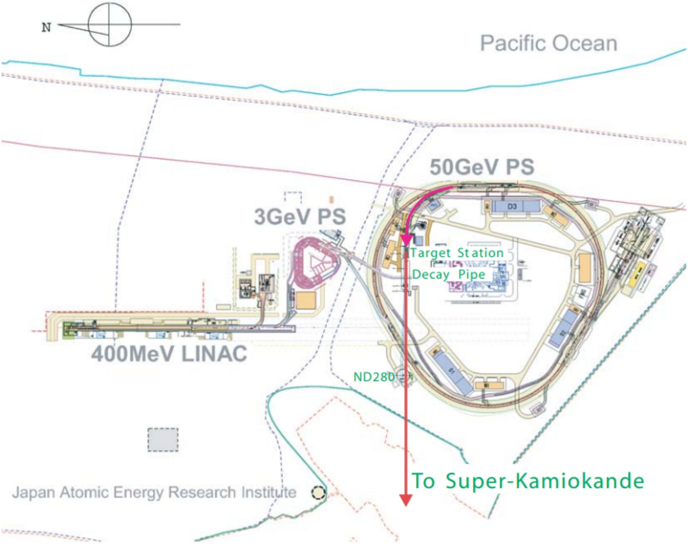
Experiment Setup

J-PARC(Japn proton accelerator research complex) consists of

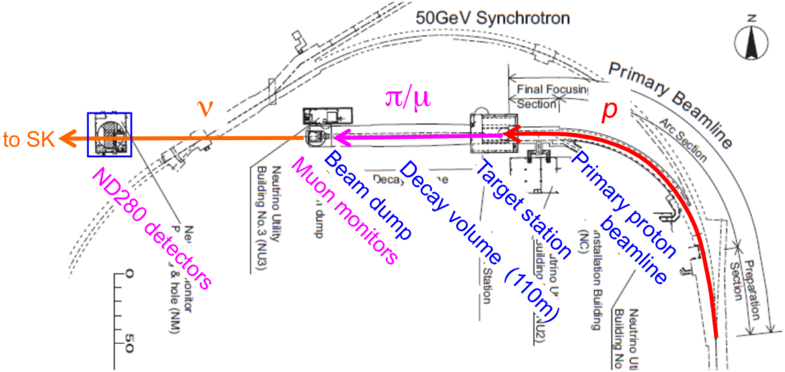
- LINC 400MeV
- RCS 3GeV
- MR 50GeV



T2K Neutrino Beamline

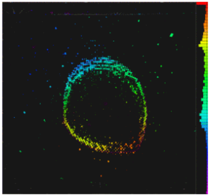


T2K Neutrino Beamline

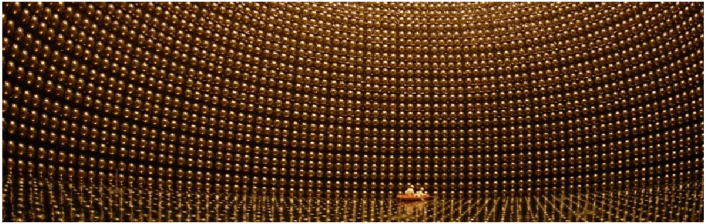


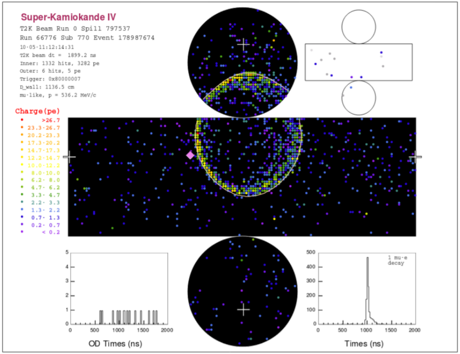
T2K Detectors - Super K

$$\nu_\mu + \text{ water } \to \mu^- \text{ or } e^- \to \text{Cherenkov radiation}$$

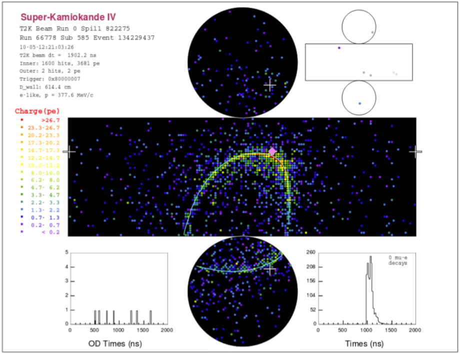


$$\begin{cases} \mu^- & \to \text{ sharp ring} \\ e^- & \to \text{ diffuse ring} \end{cases}$$





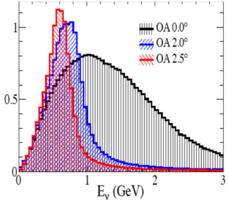
(a) muon-like event

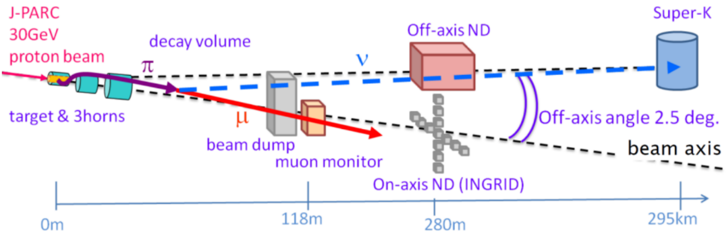


(b) electron-like event

Advantage of off-axis beam

- higher neutrinos flux
- fewer high energy neutrinos
- less contamination in beamline



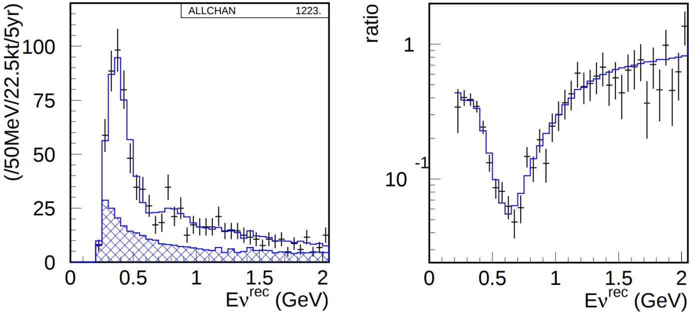


Results Data

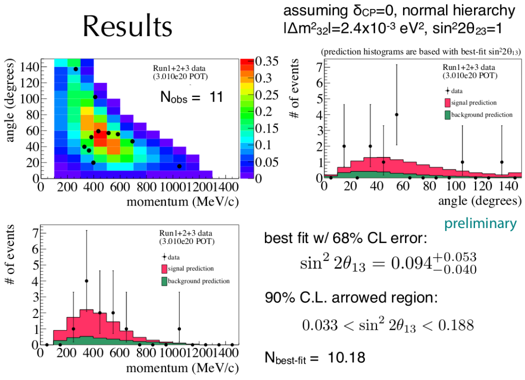
- ν_μ Disappearance
- ν_e Appearance
- CP Violation
- Possible Implication

ν_μ Disappearance

Survival probability of $\nu_\mu \rightarrow$ neutrino oscillation parameters
$(sin^2 2\theta_{23}, \Delta m^2_{23}) = (1.0, 2.7 \times 10^{-3}\text{eV}^2) \pm (0.009, 5 \times 10^{-5}\text{eV}^2)$



ν_e Appearance

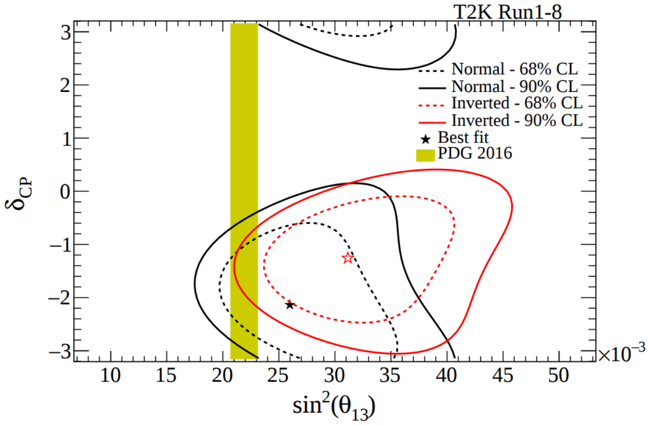


28 ν_e detected, but only 4.6 expected if no oscillation → neutrino oscillation confirms

Evidence of ν_e appearance → open a possibility to measure CP violation in lepton sector

CP Violation

Best fit: $\delta_{CP} = -1.87(-1.43)$ for normal(inverted) ordering
C.L. 2σ: (-2.99, -0.59) for normal, (-1.81, -1.01) for inverted ordering



Minimal Unitarity Violating model

To perform the test we need

- A predictive model for new physics in ν oscillation to compute asymmetries
- Experimental facilities where to make the test

Many possible choices in both cases

We decide to use:

- **Minimal Unitarity Violating model (MUV)**

MUV model

- **Main assumption:**

  the complete theory of ν oscillation is unitary but the effective low energy mixing matrix in NOT

Low energy mixing matrix

$$N = (1 + \eta) U_{PMNS}$$

Hermitian matrix: 9 new parameters

Unitary matrix: 4 independent parameters

MUV model

- The structure of the matrix elements of *N* can be obtained from <u>oscillation experiments</u> (especially disappearance) and <u>weak decays</u>

Phases unconstrained

$$N = (1+\eta) U_{PMNS}$$

$$|\eta| = \begin{pmatrix} |\eta_{ee}| < 1.5\cdot10^{-3} & |\eta_{e\mu}| < 3.6\cdot10^{-5} & |\eta_{e\tau}| < 8.0\cdot10^{-3} \\ |\eta_{\mu e}| < 3.6\cdot10^{-5} & |\eta_{\mu\mu}| < 2.5\cdot10^{-3} & |\eta_{\mu\tau}| < 4.9\cdot10^{-3} \\ |\eta_{\tau e}| < 8.0\cdot10^{-3} & |\eta_{\tau\mu}| < 4.9\cdot10^{-3} & |\eta_{\tau\tau}| < 2.5\cdot10^{-3} \end{pmatrix}$$

Main features: all new moduli at $O(10^{-2}\text{-}10^{-3})$ but $\eta_{e\mu}$ which is of $O(10^{-5})$

7