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Final Report

CP violation in neutrino oscillation recently reported by T2K

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Outline:

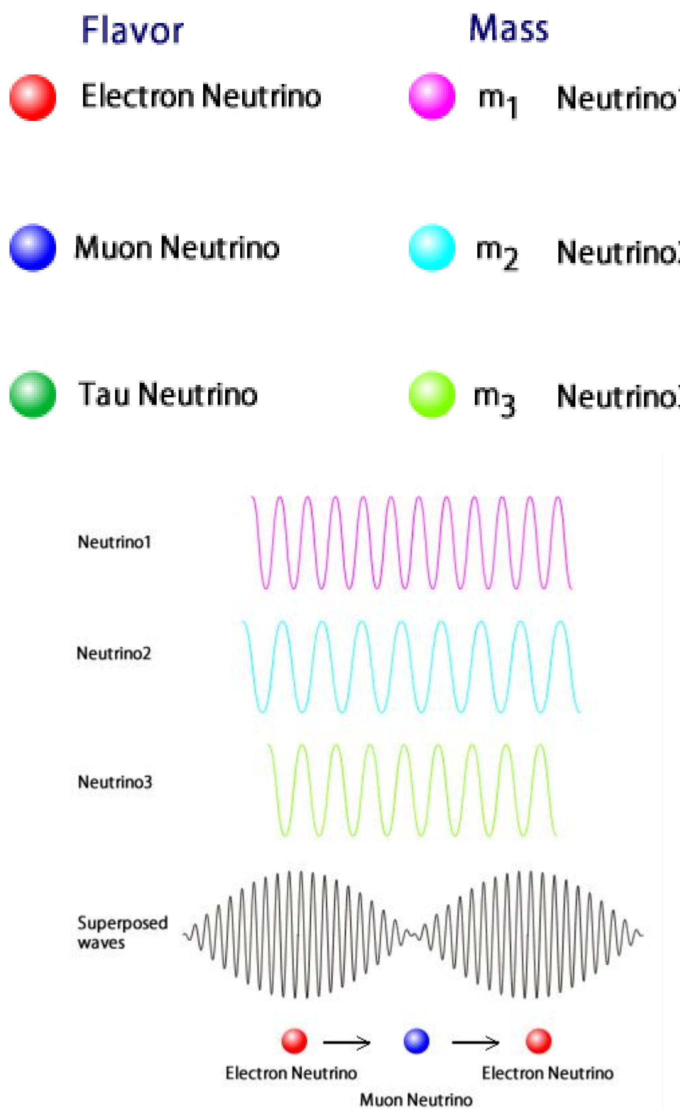
1. Physics Motivation

2. About T2K Experiment

3. A Review of T2K's Results

4. Next Generation Neutrino CPV Experiments

Physics Motivation: Neutrino oscillation in a nutshell



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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

Neutrino oscillation occurs when neutrinos have mass and non-zero mixing.

http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

Six parameters which govern neutrino oscillation:

θ_{12} θ_{13} θ_{23} δ_{CP} Δm^2_{21} Δm^2_{31}

$$\mathrm{P}\left(\nu_\mu \rightarrow \nu_e\right) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right) \mp \frac{1.27\Delta m^2_{21}L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right).$$

J_{cp} is appoximately $0.033\sin\delta_{CP}$

The second term in Equation has a negative sign for neutrinos and a positive sign for antineutrinos.

Measuring how many of (anti-)neutrinos have changed their flavor is the theoretical basis of T2K experiment.

Neutrino CPV, Seesaw Mechanism and leptogenesis

Prevalence of matter needs a heavy particle decaying to produce particles more than antiparticles due to CPV

↓

Neutrino has minuscule mass

↓

Seesaw mechanism: if a right-handed neutrino is heavy, the left-handed partner must be light.

↓

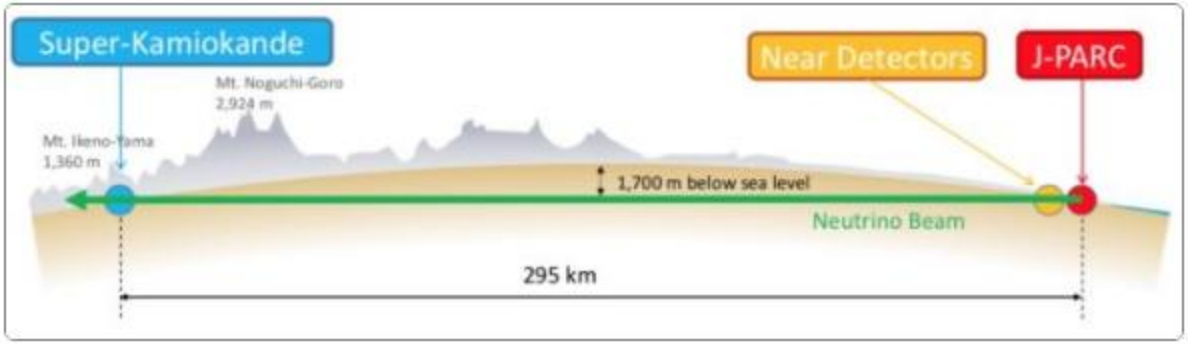
A heavy right-handed neutrino is its own particle, whose decay can satisfy theory's need. The heavy particle might be the heavy partner of light neutrino we observe!

↓

Leptogenesis: convert the lepton–anti-lepton imbalance to a baryon–anti-baryon asymmetry.

About T2K experiment

Pictures from: https://t2k-experiment.org/t2k/



Uses beams of muon neutrinos and antineutrinos, with energy spectra peaked at 0.6 GeV

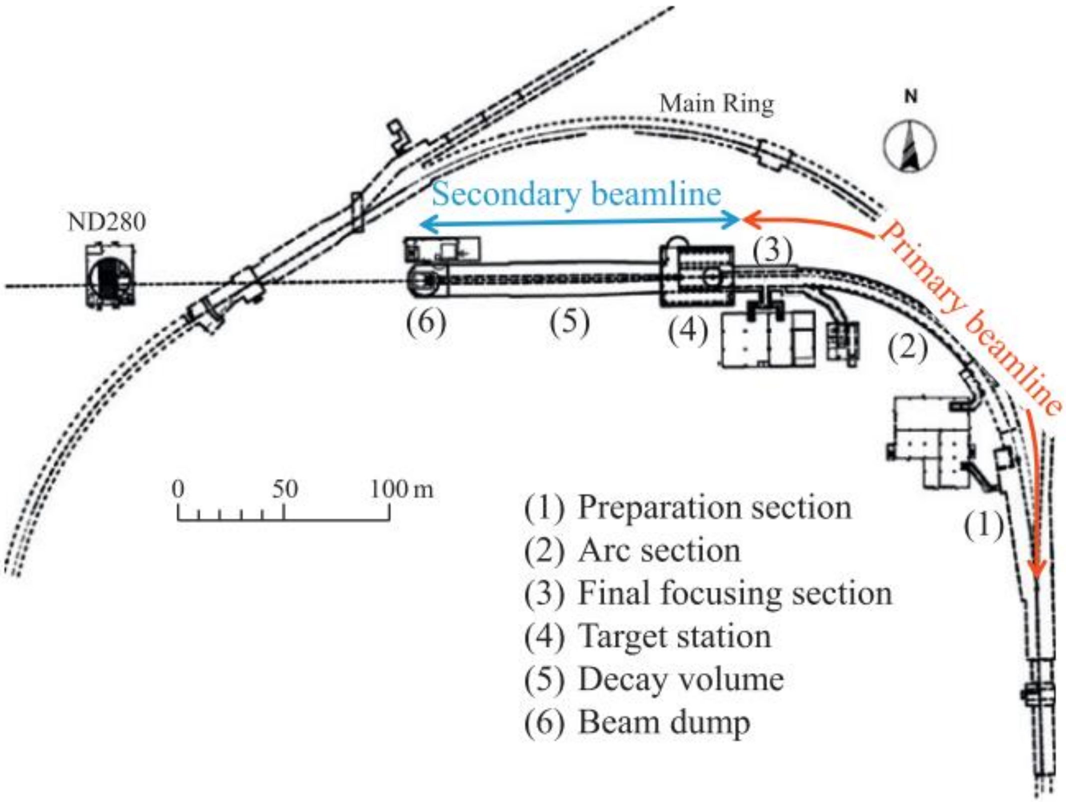
Two near detectors:

Ingrid: located on the beam axis, monitors the direction and stability of the neutrino beam.

ND 280: located 2.5 ◦ away from the beam axis, used to predict the number of muon neutrinos that would be seen in the "far detector" SuperKamiokande if there were no oscillations.

Far detector SK: located at the same angle away from the beam axis as ND280, can distinguish muons from electrons.

The Neutrino Production
arxiv:1106.1238



Machine design parameters of the J-PARC MR for the fast extraction.

Circumference	1567 m
Beam power	~ 750 kW
Beam kinetic energy	30 GeV
Beam intensity	~ 3×10^{14} p/spill
Spill cycle	~ 0.5 Hz
Number of bunches	8/spill
RF frequency	1.67–1.72 MHz
Spill width	~ 5 µs

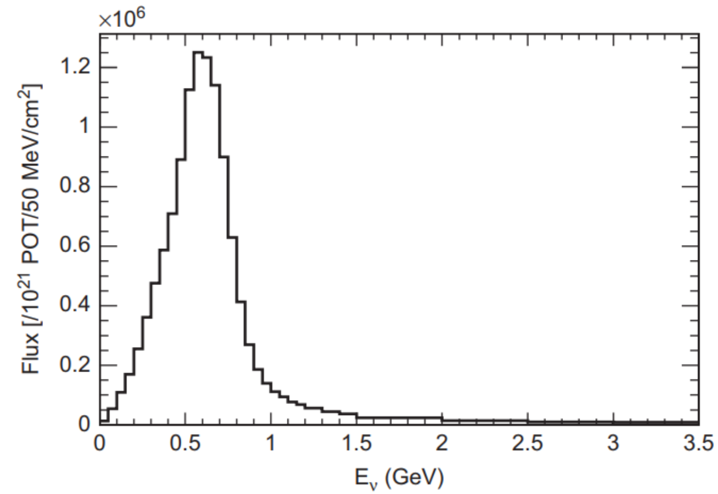
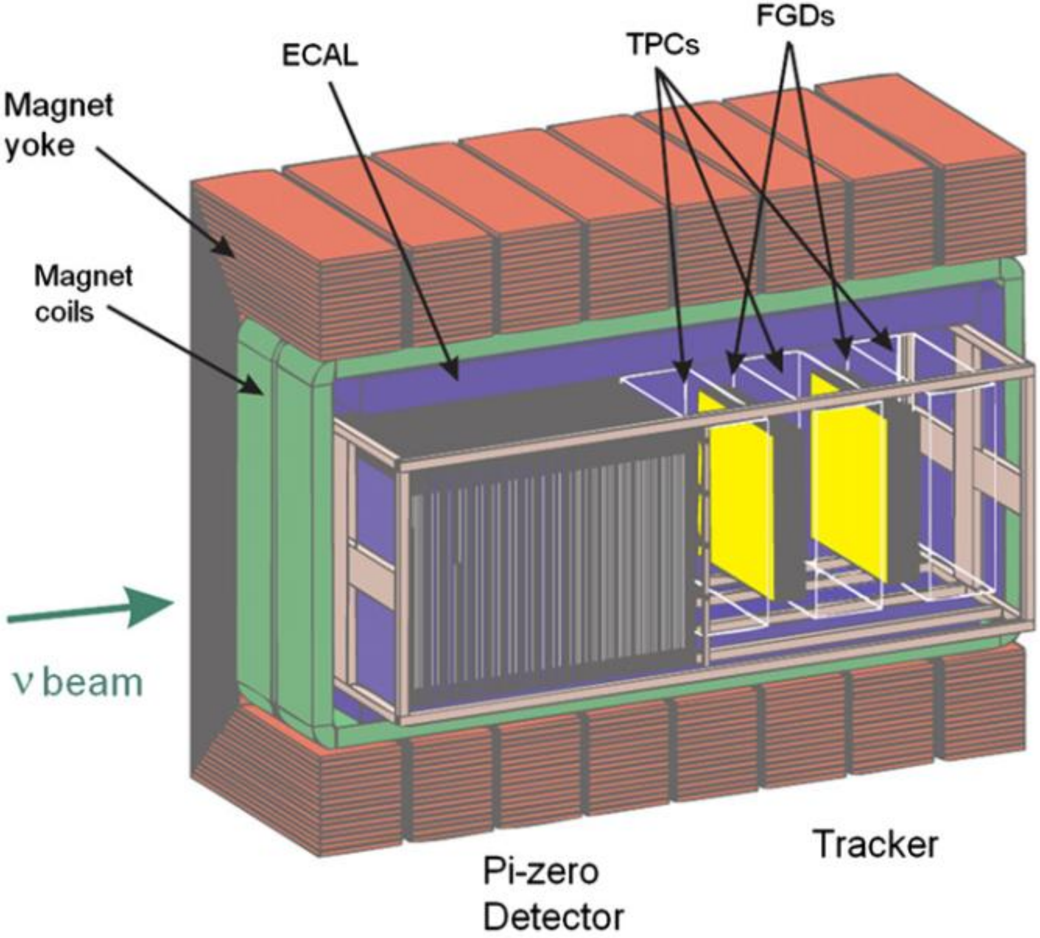


Fig. 3. The unoscillated ν_μ flux at Super-Kamiokande with an off-axis angle of 2.5° when the electromagnetic horns are operated at 250 kA.

Producing beams of muon neutrinos and antineutrinos, with energy spectra peaked at 0.6 GeV

Near Detector: ND280
arxiv:1204.3666

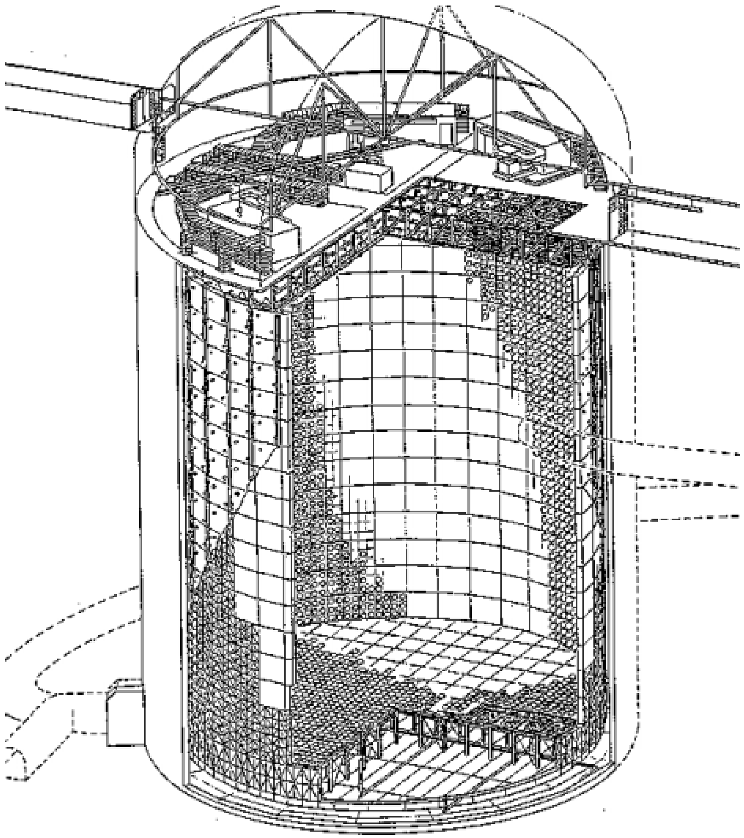


An innovation: first off-axis detector, can provide narrow-band beam and low background rates.

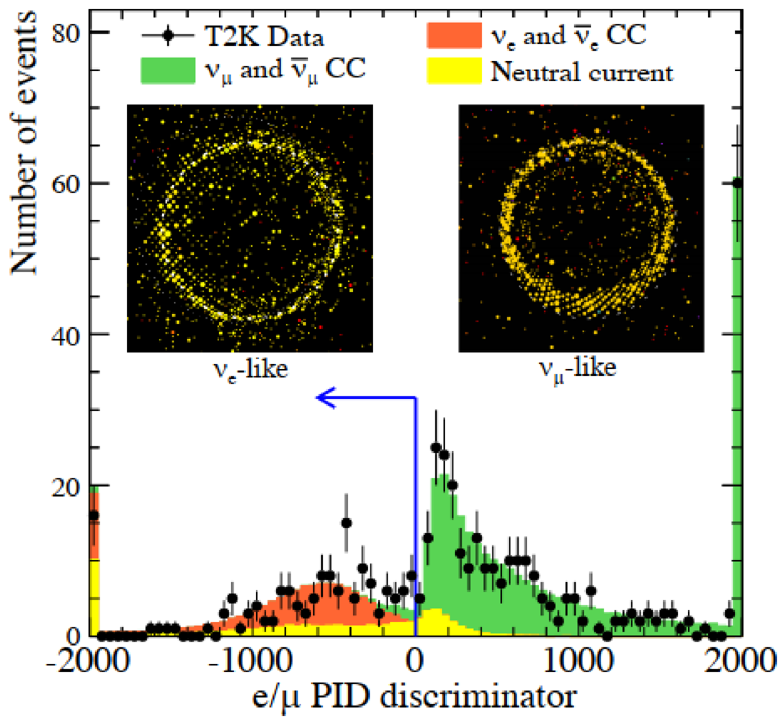
The tracker: measures charged current neutrino interactions such as:
$\upsilon_l + N \rightarrow l^- + N' + \pi$

The Pi-zero detector: to identify π0.
$(\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0 + X)$

Far Detector: Super-Kamiokande



Arxiv:hep-ex/0501064v2
A drawing of the Super-Kamiokande detector. The cutaway shows the inside lined with photomultiplier tubes comprising a photocathode coverage of about 40%.



Arxiv: 1910.03887
Main process: CCQE interactions:
$\nu_l + n \rightarrow l^- + p$
Background: $\upsilon_l + N \rightarrow l^- + N' + \pi$
$(\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0 + X)$
Event selection: events with a single charged lepton in the final state.

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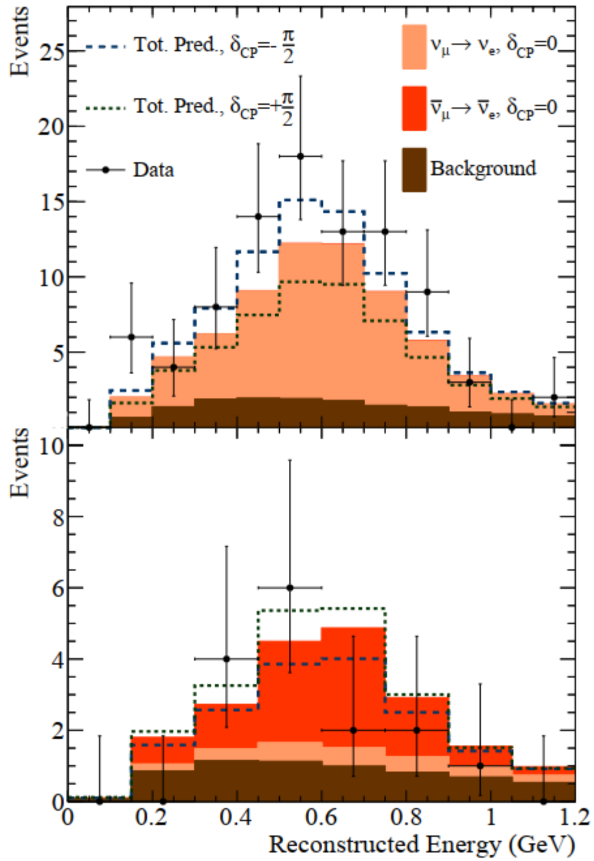
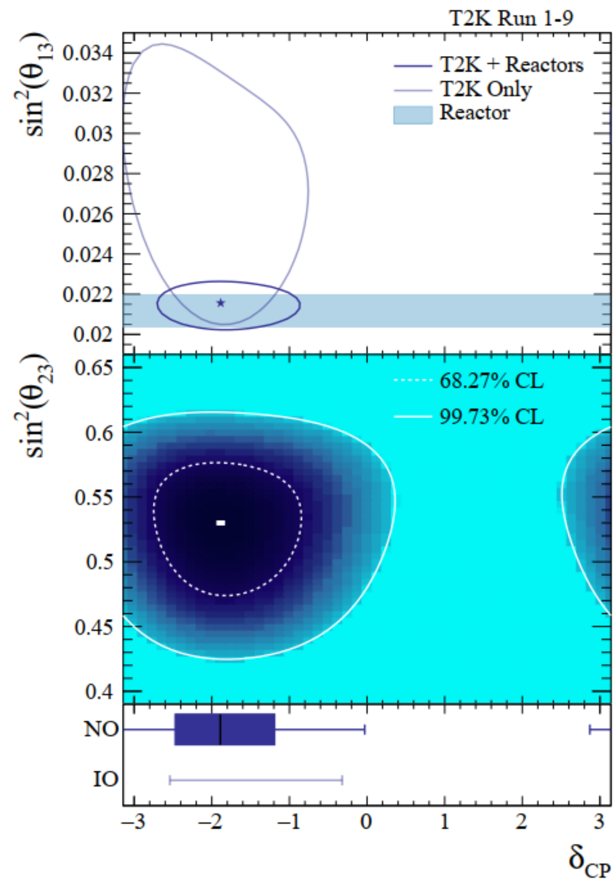
A Review of T2K's Results
arxiv: 1910.03887





For δ_{CP}, the best fit value and 68% uncertainties assuming the normal (inverted) mass ordering are $-1.89^{+0.70}_{-0.58}(-1.38^{+0.48}_{-0.54})$ .The CP conservation points are excluded at 95% confidence level. 46%(65%) of the parameter space are excluded for the normal (inverted) ordering at three confidence and credible intervals.

Next Generation Neutrino CPV Experiments

Table from Takaaki Kajita, Nuphys 2019 London, UK Dec.16, 2019

	DUNE	Hyper-K
Baseline	1300km ➔ Large matter effect (Good for Mass Ordering determination)	295km ➔ Small matter effect (Smaller effect of matter density uncertainty in δ_{CP})
Beam energy	~ Multi-GeV	~ Sub-GeV
Detector technology	Liq. Ar TPC	Water Cherenkov

DUNE's advantage: Liquid Argon TPC, enhanced resolution and greater efficiency in distinguishing signal events from background.

Hyper K's advantage: excellent sensitivity of its detectors, The total (fiducial) mass of one tank is 258 (187) kilo-tons, which is about 20 times larger than that of Super -Kamiokande and more 10 times larger than competing projects (10 times DUNE, 40 kt, or 20 times JUNO, 20 kt).

Both of them have upgraded beam power of protons to more than 1.2 MW, compared to 0.75 MW of T2K.

Thanks!