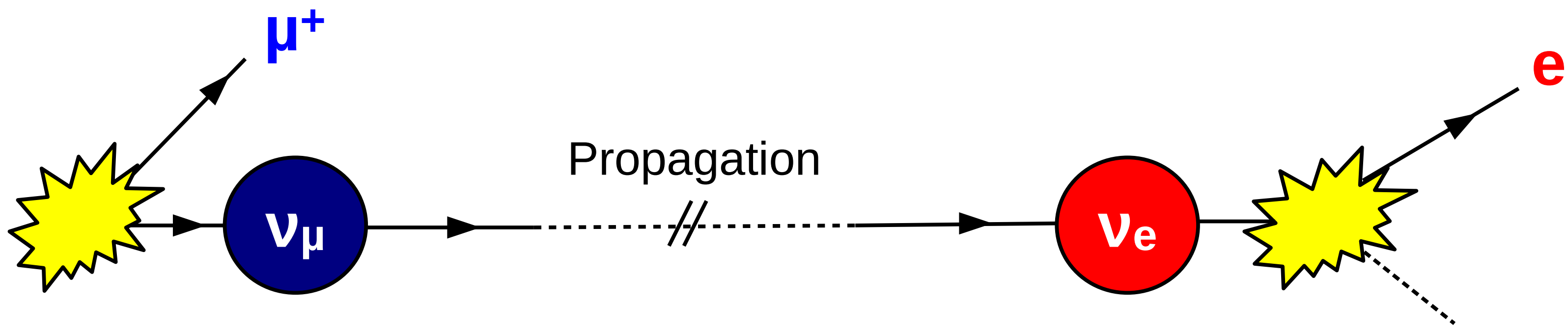
Research Results Presentation Meeting of the Inter-University Research Program for FY2024

Tokai to Kamioka Long Baseline Neutrino Experiment (T2K)

C. Bronner on behalf of the T2K collaboration
January 29th, 2025

Institute for Cosmic Ray Research
University of Tokyo

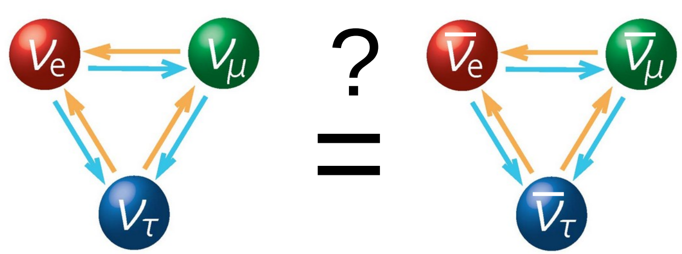
Physics Goals: Neutrino Oscillations



- Precise measurement of parameters describing $\nu_\mu \to \nu_X$ "disappearance": θ_{23}, Δm^2_{32}
- Study of the 3 main open questions in neutrino oscillations

CP symmetry

- difference matter/anti-matter

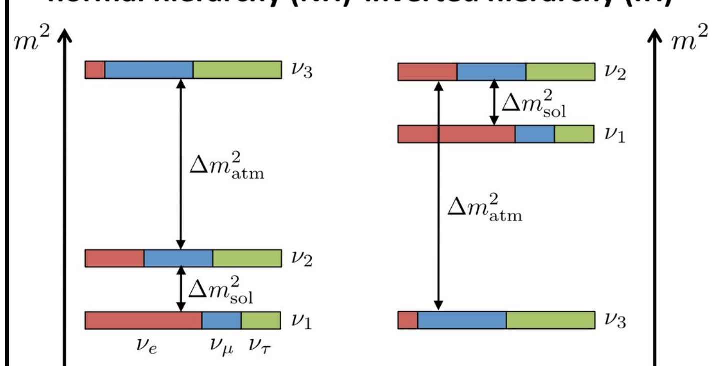


In standard neutrino oscillations:

$\not{CP} \Leftrightarrow$ **sin(δ) ≠ 0**

Mass ordering

- Neutrino mass models
- input for other experiments (0νββ, supernova)

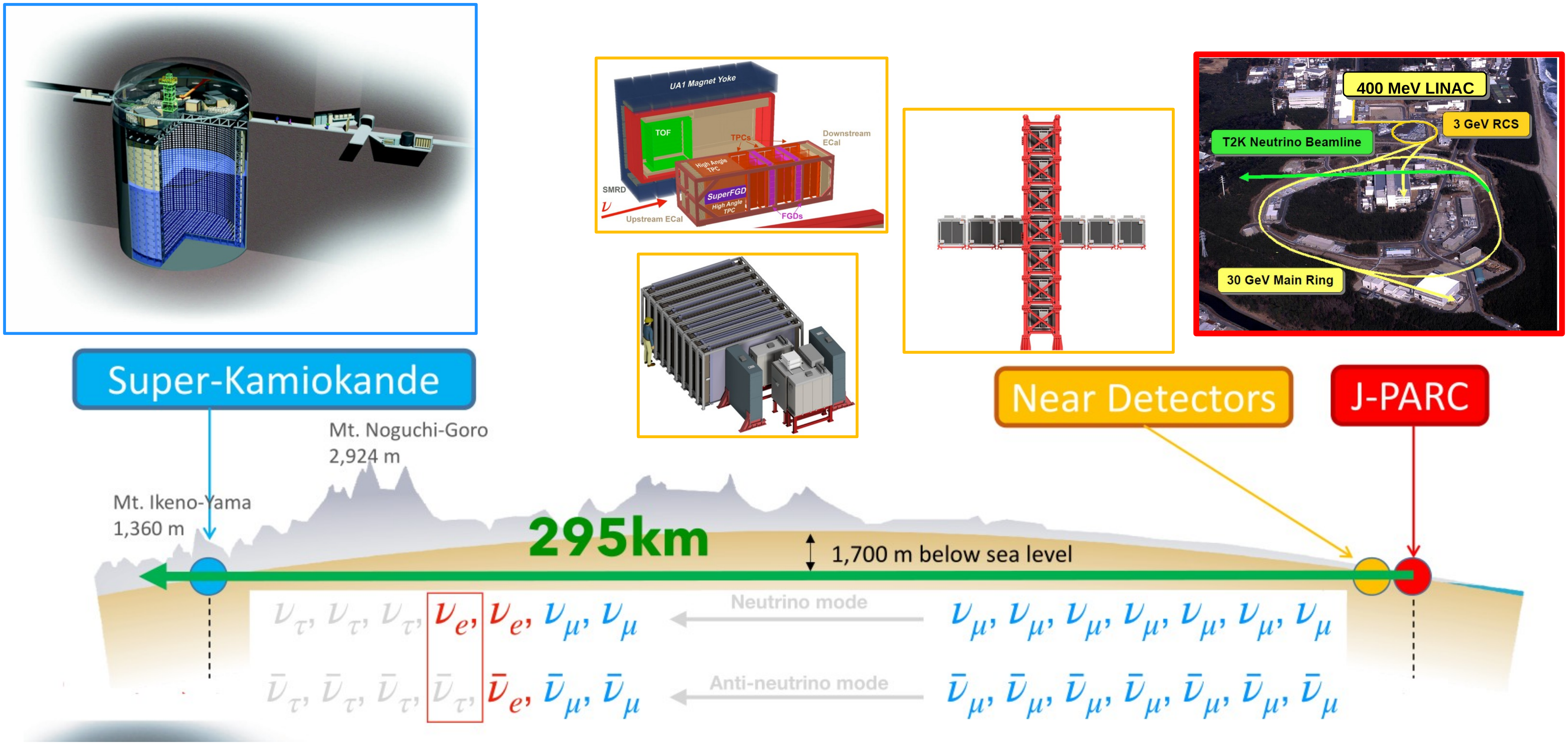


Octant of θ_{23}

- symmetries in lepton sector

$\theta_{23} > \pi/4$?
$\theta_{23} = \pi/4$?
$\theta_{23} < \pi/4$?

Experiment overview



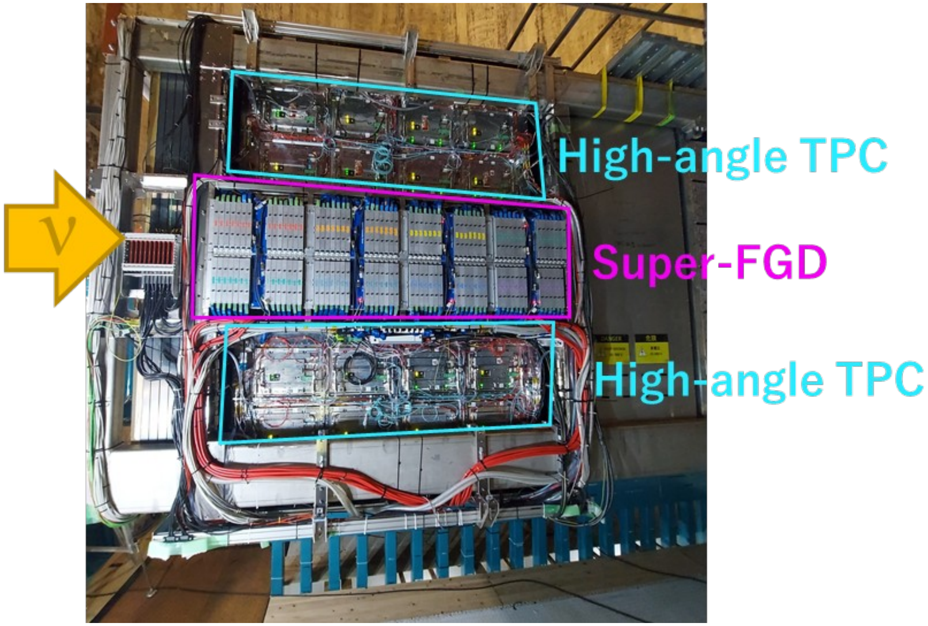
Far detector:
- Observe neutrinos after propagation
- **Study oscillations**

- ➔ ν beam monitoring
- ➔ Constrain uncertainties
- ➔ **ν interaction measurements**

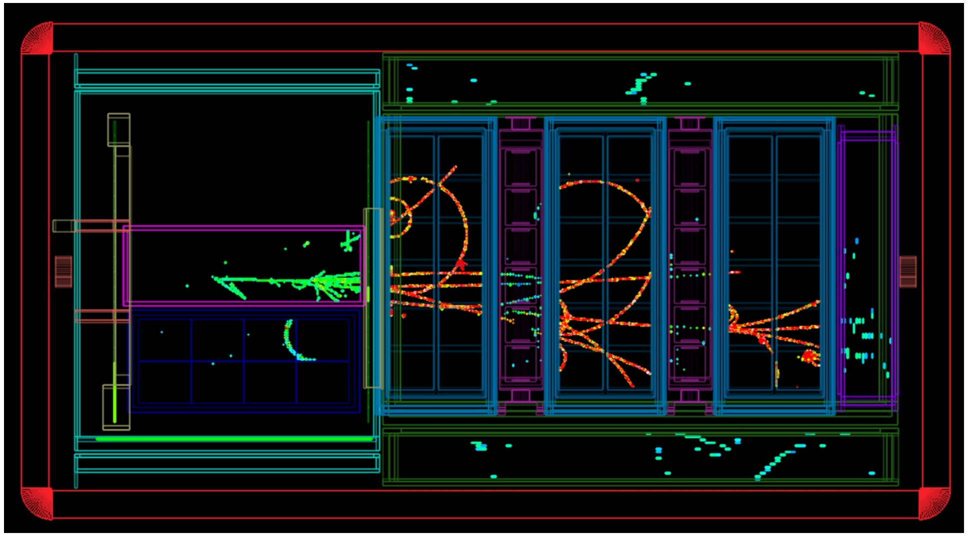
Neutrino beam production

Near detector upgrade

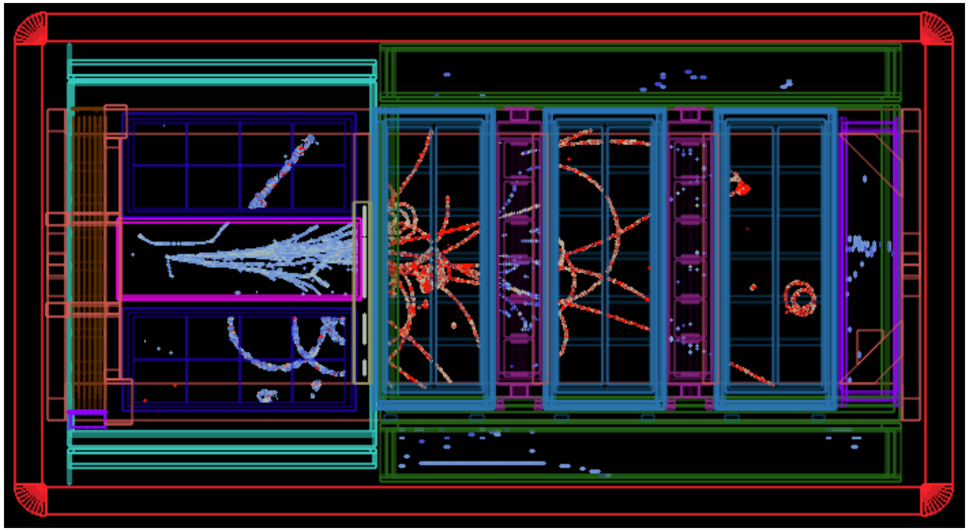
- Significant T2K project over a number of years
- Will bring increased ability to study neutrino interactions
- Detector installation completed beginning of FY2024
- Data taking with full detector started June 2024



December 2023

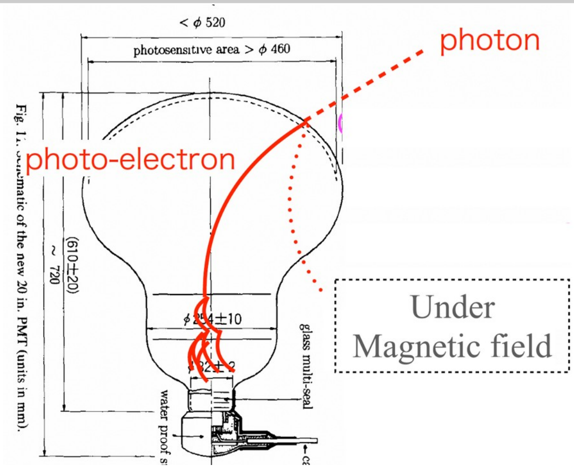


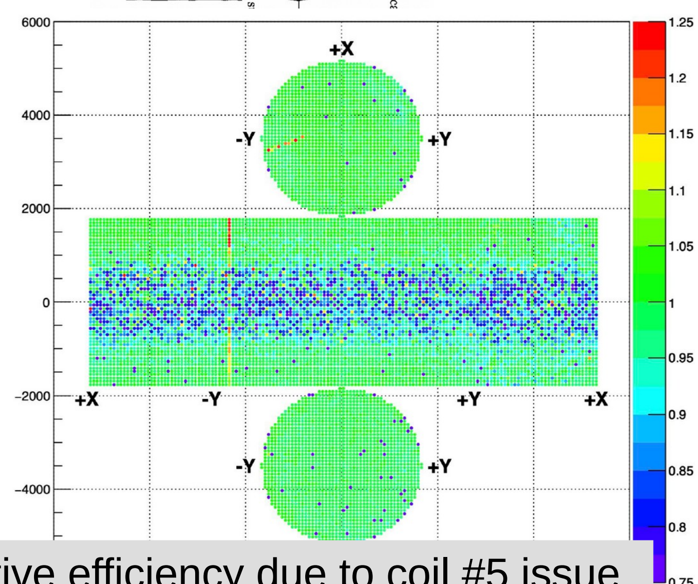
June 2024



SK geomagnetic compensation coil issues

- Super-K uses a system of coils to compensate geomagnetic field which would otherwise affect PMT detection efficiency and response
- A number of coils failures at the end of 2023.
- Some could be repaired directly, but not one located in the middle of the detector
- Was finally fixed during summer 2024
- Modified analysis to be able to use data taken during this problem in preparation

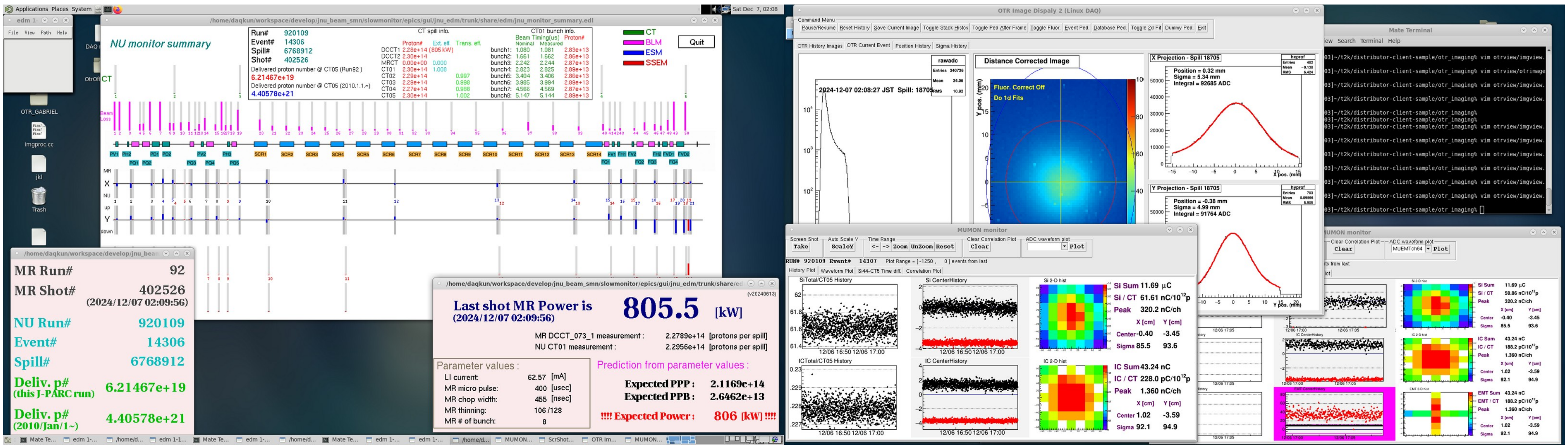




Relative efficiency due to coil #5 issue

Data taking

Several data taking periods in FY2024
- First took data in June 2024, with full NDUpgrade detector but SK coil issue
- Data taking with SK coils repaired from end of Nov. 2024

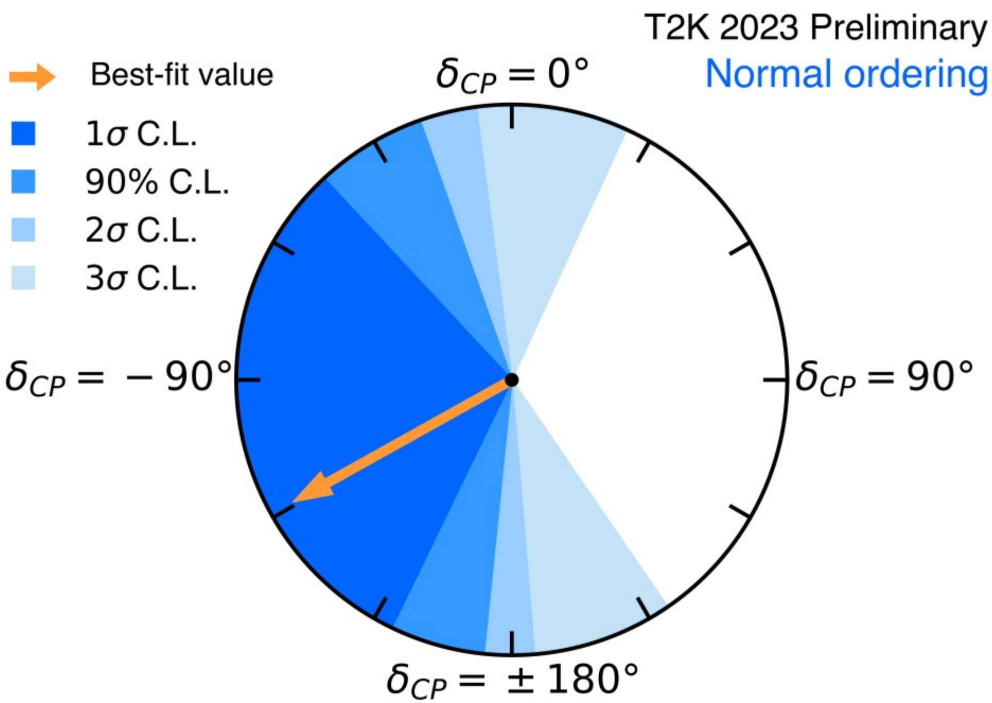


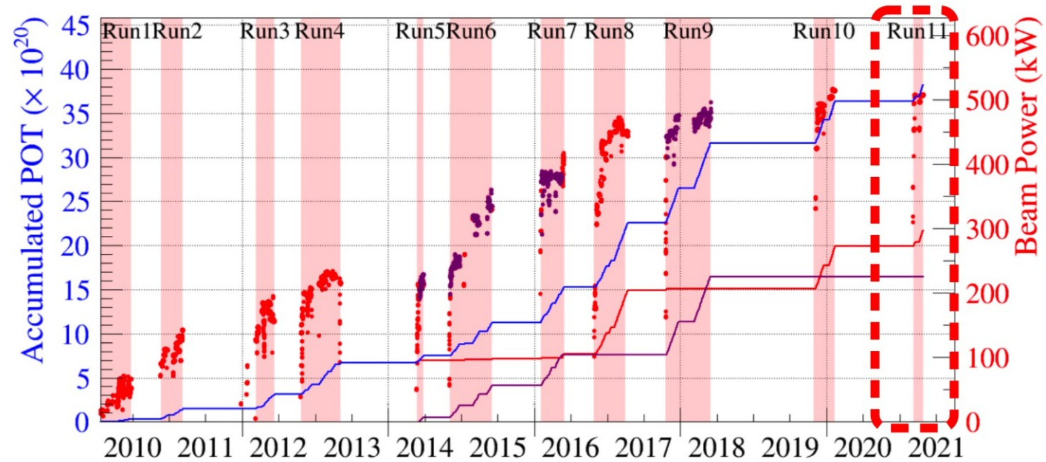
- Achieved stable operation at 805 kW
  Collected 2.26e20 POT between 2024/11/25 and 2024/12/23
- Collected data in anti-neutrino running mode for the first time since 2017
- Additional data taking this fiscal year in Feb.-Mar.

New oscillation results: run 1-11 analysis

T2K presented a new neutrino oscillation result at neutrino 2024 conference:
- First use of data with Gd dissolved in SK water
- Increases neutrino-mode data by 9%
- Improved detector model for far detector

Conservation of CP symmetry excluded at 90% CL





Far detector systematic uncertainty

Sample	OA22	New results
ν-mode 1Rμ	3.4%	3.2%
ν-mode 1Re	5.2%	4.9%
ν-mode MR	4.9%	3.9%
ν-mode 1Re+d.e.	14.3%	6.3%
$\bar{\nu}$-mode 1Rμ	3.9%	5.0%
$\bar{\nu}$-mode 1Re	5.8%	6.7%

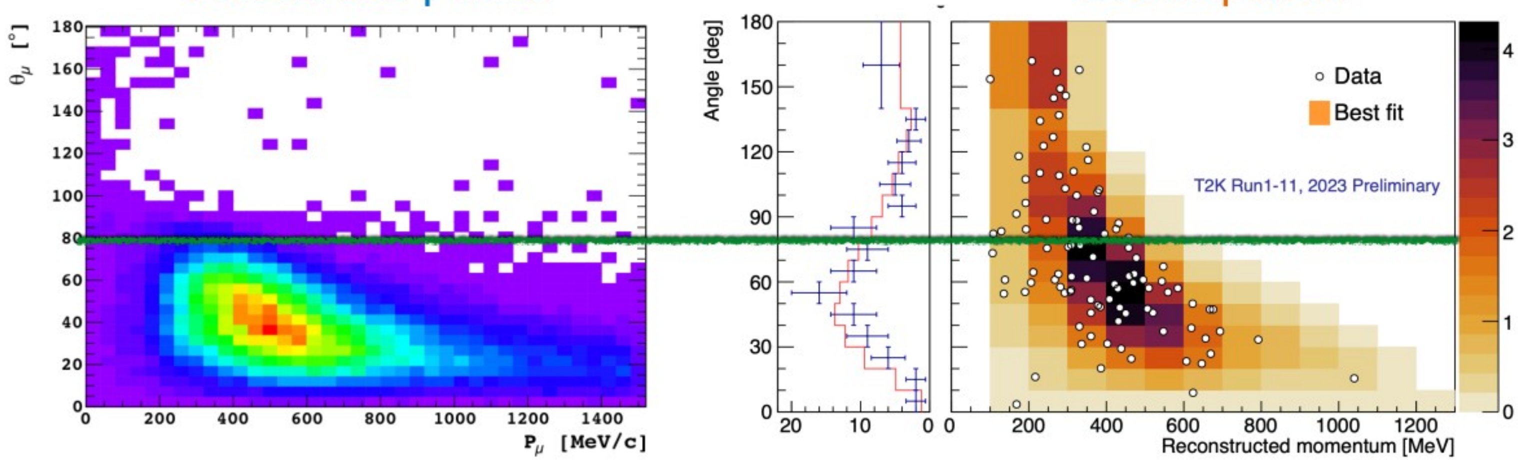
C. Giganti @ Neutrino 2024
D. Carabadjac @ ICHEP 2024

Analysis update in preparation

- New oscillation analysis in preparation
- On near-detector side:
  - ➔ Updated neutrino interaction model
  - ➔ Use “4π” event selections to better match SK acceptance
- MC only part of this new ND analysis was presented at neutrino 2024

ND280 acceptance

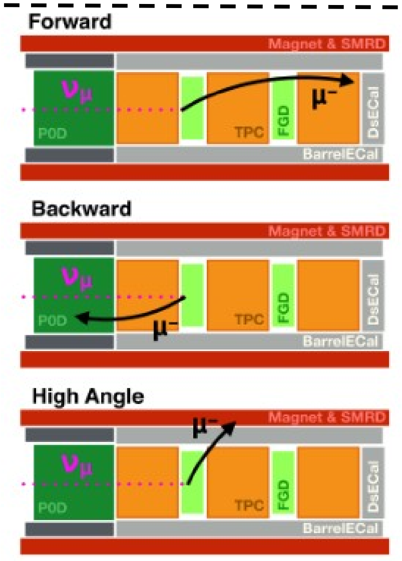
SK acceptance

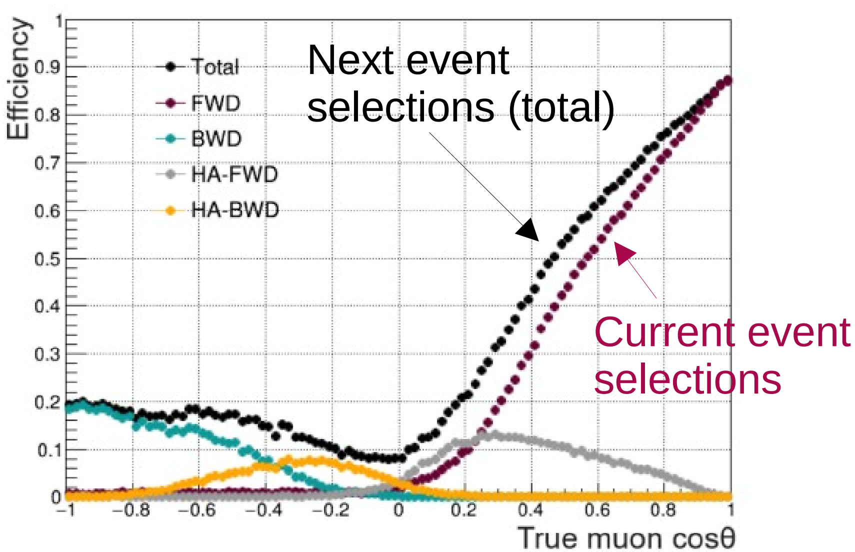


Current analysis

Next analysis

- 0 -> ~20% efficiency in backward region
- Will be further improved by ND upgrade

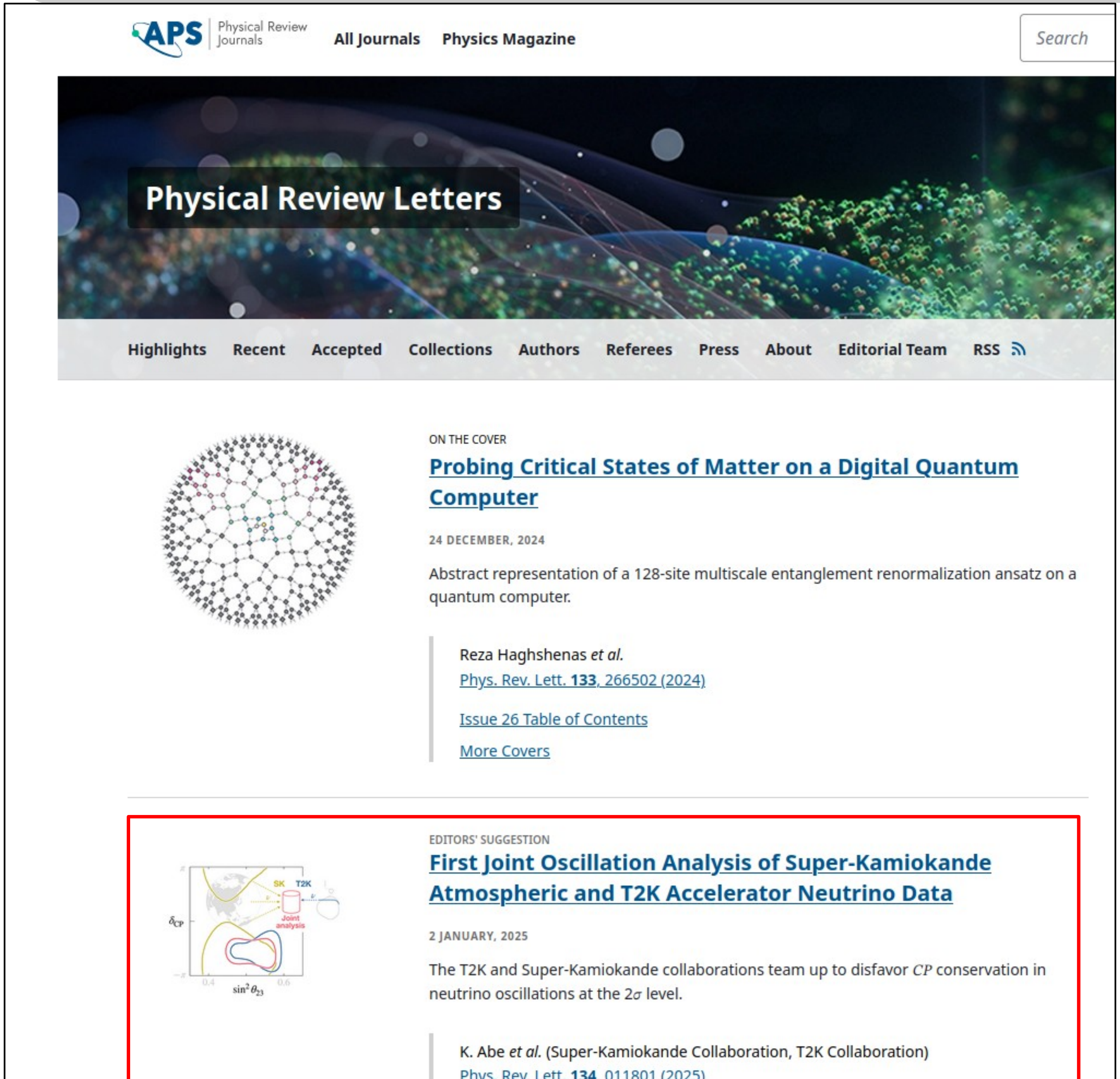




C. Giganti @ Neutrino 2024

Publication: joint analysis with SK atmospheric

Result of the first joint analysis of T2K and Super-Kamiokande data was published in PRL as Editor's suggestion: Phys. Rev. Lett **134**, 011801 (2025)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ON THE COVER

Probing Critical States of Matter on a Digital Quantum Computer

24 DECEMBER, 2024

Abstract representation of a 128-site multiscale entanglement renormalization ansatz on a quantum computer.

Reza Haghshenas *et al.*

Phys. Rev. Lett. **133**, 266502 (2024)

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More Covers

EDITORS' SUGGESTION

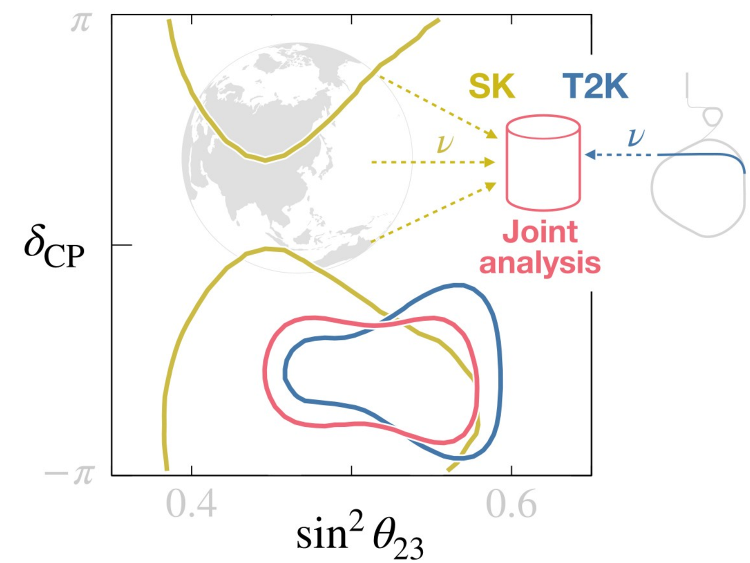
First Joint Oscillation Analysis of Super-Kamiokande Atmospheric and T2K Accelerator Neutrino Data

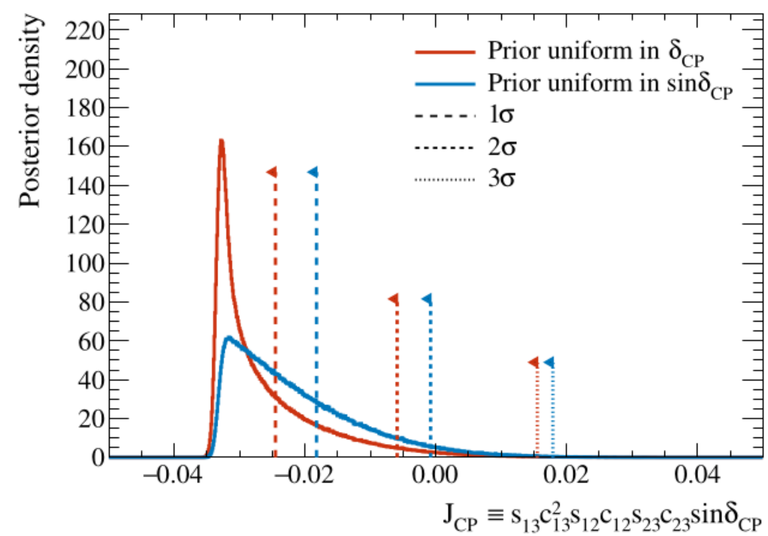
2 JANUARY, 2025

The T2K and Super-Kamiokande collaborations team up to disfavor *CP* conservation in neutrino oscillations at the 2σ level.

K. Abe *et al.* (Super-Kamiokande Collaboration, T2K Collaboration)

Phys. Rev. Lett. **134**, 011801 (2025)





Conservation of CP symmetry excluded at 1.9-2.0σ level

Budget

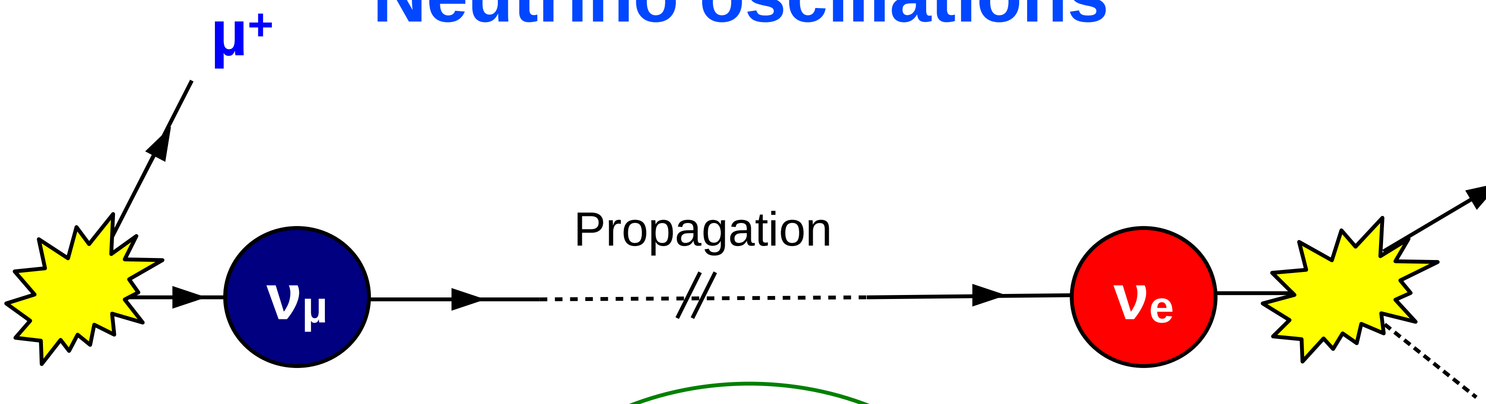
- T2K received 100,000 JPY in JFY2024 from ICRR Inter-University Research Program
- This budget was used for travels to Kamioka
- We are very grateful for this support

Summary

- T2K studies neutrino oscillations, in particular the open questions of CP symmetry and mass ordering using a beam of neutrinos produced by an accelerator
- Upgrade of near detector was completed, first data with full detector in June 2024
- Part of the data taken in FY2024 were affected by SK geomagnetic coil problem. After installation of new coils in summer 2024, successful data taking in Nov.-Dec., with additional data taking planned by the end of the FY
- During this period, reached stable beam operation at 805 kW
- New oscillation analysis results presented at neutrino 2024, using 9% additional data and improved far detector model
- New analysis in preparation, using for the first time “4π” selections at the near detector
- First joint analysis of T2K and Super-K atmospheric data was published in PRL

BACKUP

Neutrino oscillations



Flavor eigenstates (interaction)

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

Mass eigenstates (propagation)

Mixing (or Pontecorvo-Maki-Nagawa-Sakata) matrix
link between the two sets of eigenstates

> $P(\nu_\alpha \rightarrow \nu_\beta)$ oscillates as a function of distance L traveled by the neutrino with periodicity $\mathbf{\Delta m^2_{ij} L/E}$

$(\Delta m^2_{ij} = m^2_i - m^2_j)$

Neutrino oscillations Parameters

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

$P(\nu_\alpha \rightarrow \nu_\beta)$ depends on 6 parameters:

- 3 **mixing angles** : **θ_{12}, θ_{23}, θ_{13}** → Amplitude
- 2 **mass splittings** : **Δm^2_{ij}** → Periodicity
- 1 (complex) phase : The **CP phase δ** → Difference in oscillations $\nu/\bar{\nu}$

$$P(\nu_\alpha \rightarrow \nu_\beta, U) = P(\overline{\nu_\alpha} \rightarrow \overline{\nu_\beta}, U^*)$$