News from T2K

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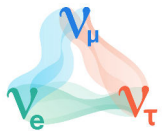
High Energy Accelerator Research Organization (KEK)

6th New Physics Opportunities at Neutrino Facilities Workshop
May 26, 2026

Neutrino oscillations

flavour eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates

Neutrino mixing is parametrized by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric \& accelerator}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix}}_{\text{reactor \& accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar \& reactor}}$$

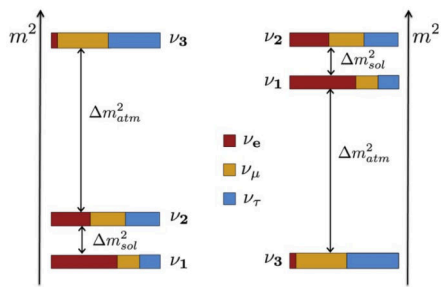
$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

+ two mass-squared differences $\Delta m^2_{32} = m^2_3 - m^2_2$, $\Delta m^2_{21} = m^2_2 - m^2_1$,

Open questions in ν oscillations

T2K (among other long-baseline neutrino experiments with $L/E \sim 10^{2-3}\mathrm{km/GeV}$) can help answer the following questions:

- What is the mass hierarchy of Δm^2_{32}?
  - ν_3 heavier than $\nu_2 \longrightarrow$ normal ordering (NO)
  - ν_3 lighter than $\nu_2 \longrightarrow$ inverted ordering (IO)
- Is θ_{23} greater than, smaller than, or equal to 45°?
- Is CP symmetry violated in the neutrino sector ($\sin\delta_{\mathrm{CP}} \neq 0$), and what is the value of δ_{CP}?

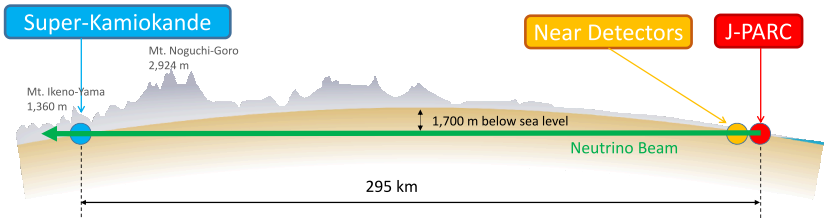


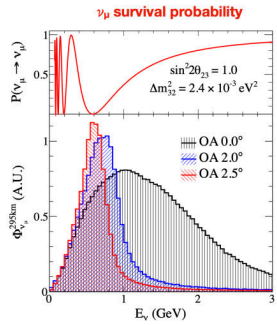
The T2K experiment

The Collaboration

~560 members, 75 institutes, 15 countries

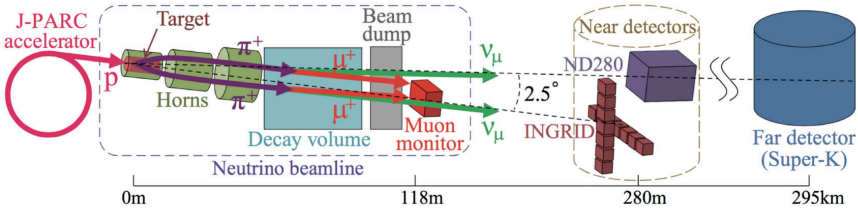
Experiment Overview





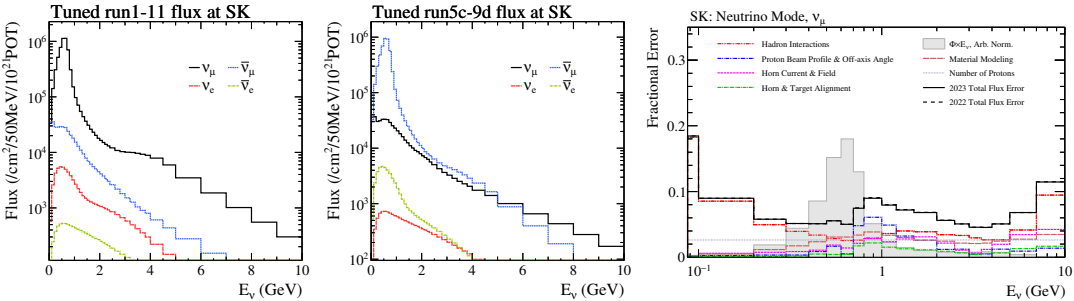
- High intensity $\nu_\mu/\bar{\nu}_\mu$ beam produced at J-PARC
- Near detectors placed 280 m from the production target measure un-oscillated neutrinos
- Far detector (Super Kamiokande), 295 km from the production target, measures oscillated neutrinos
- Off-axis technique is employed $\longrightarrow$ narrow-band beam peaked at around 600 MeV, corresponding to the oscillation maximum at the Far Detector

T2K beamline



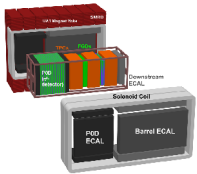
- A high-intensity 30 GeV proton beam from the J-PARC Main Ring strikes a graphite target, producing secondary particles (mainly pions and kaons).
- A set of 3 electromagnetic horns selectively focuses π^+/π^- to give:
  - neutrino beam from $\pi^+ \to \mu^+ + \nu_\mu$
  - antineutrino beam from $\pi^- \to \mu^- + \bar{\nu}_\mu$
- J-PARC neutrino beam is very pure: contamination of intrinsic $\nu_e/\bar{\nu}_e$ is $< 1\%$ at the peak neutrino energy

Neutrino flux (250kA horn current)



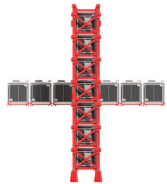
- Neutrino flux predictions obtained from measured beam parameters and MC simulations, tuned with dedicated hadron production measurements
- NA61/SHINE data with T2K replica target allowed to reduce the hadronic part of systematics $\sim 20\% \rightarrow \sim 5\%$. Eur. Phys. J. C 79, 100 (2019)
- A new large-statistics T2K replica-target dataset was collected recently by NA61/SHINE in 2022$\rightarrow$ a further reduction in flux uncertainties is expected

Near detectors



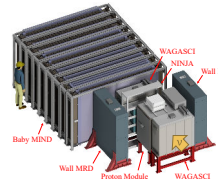
ND280 (2.5° off-axis)

- Scintillator (active) and water (passive) targets - FGDs
- Tracking with TPCs
- Magnetised, for charge and momentum measurement
- Constrains flux and cross-section systematics in T2K oscillation analyses



INGRID (on-axis)

- Iron-scintillator sandwich
- Monitors neutrino beam intensity and direction
- Also capable of cross section measurements

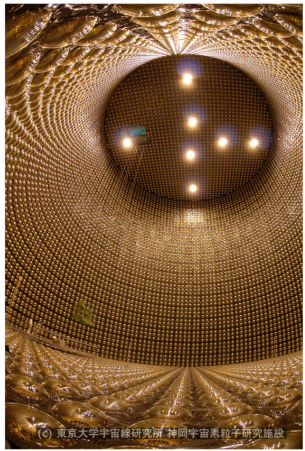


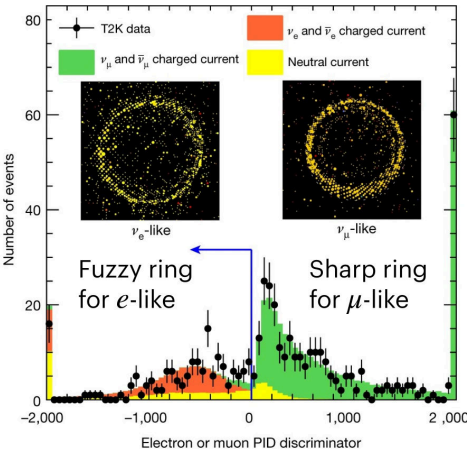
WAGASCI/BabyMIND (1.5° off-axis)

- 3D scintillator lattice for 4π angular acceptance
- Compact, magnetised iron muon range detector
- Water and scintillator target for neutrino cross-section measurements

Super-K (far detector)

- 50 kiloton water Cherenkov detector instrumented with 13k PMTs
- Cherenkov ring reconstruction from PMT charge and timing
- e vs μ PID by ring pattern
- Observes the T2K neutrino beam after oscillations
- Doped with Gd since 2020 for neutron tagging



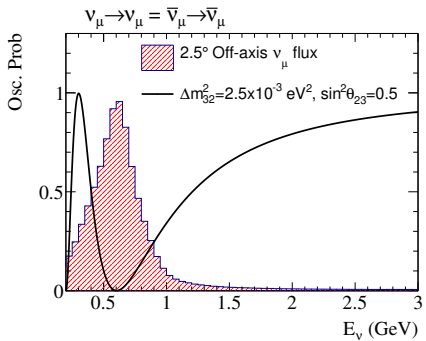


Oscillation Analysis

Oscillation measurements at T2K

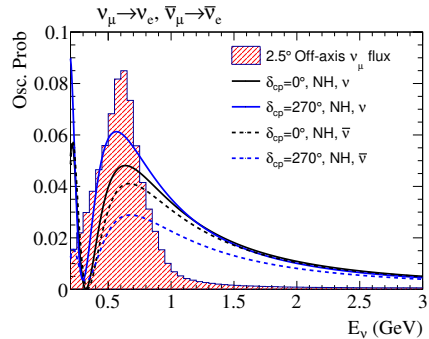
ν_μ disappearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

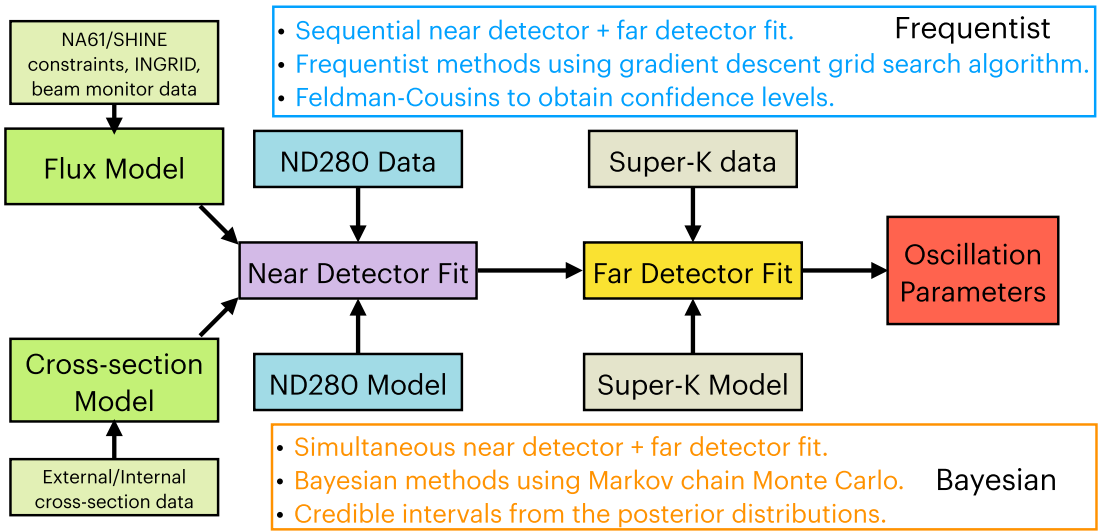


ν_e appearance

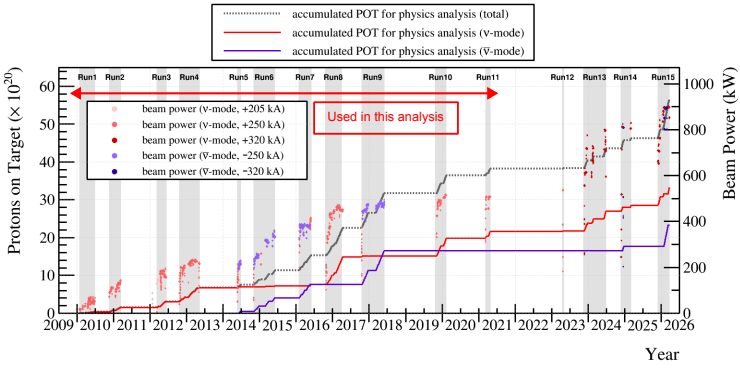
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \overset{-}{}_{(+)} O(\sin\delta_{\mathrm{CP}})$$



Analysis strategies



T2K dataset

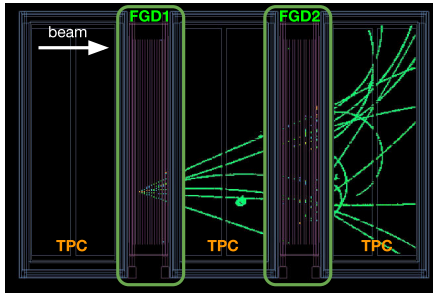


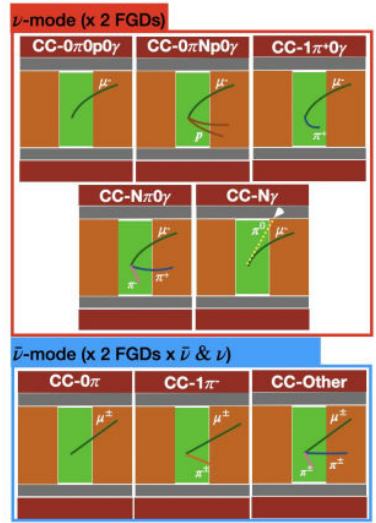
- $3.8 \cdot 10^{21}$ POT in total used for the presented analysis ($2.2 \cdot 10^{21}$ in ν mode and $1.6 \cdot 10^{21}$ in $\bar{\nu}$ mode)
- Compared to the previous T2K oscillation analysis analysis:
  - 10% more data in ν mode for SK samples,
  - Improved treatment of SK detector uncertainties
- As of today, T2K accumulated $5.7 \cdot 10^{21}$ ($3.3 \cdot 10^{21}$ in ν mode and $2.4 \cdot 10^{21}$ in $\bar{\nu}$ mode)

Near detector samples

22 samples selected based on event topology:

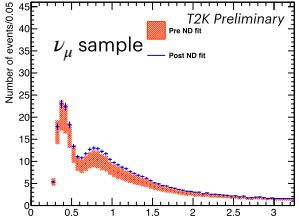
- distinguishing between ν and $\bar{\nu}$ interactions
- number of reconstructed pions
- tagging of produced pions and photons

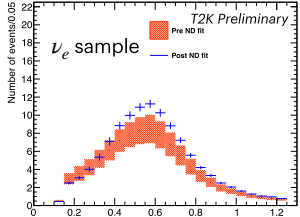




Near detector fit

- Extended binned likelihood fit to the number of selected events in all 22 samples as a function of muon kinematics
- Tune MC and constrain parameters
- Reduced systematic uncertainties on the far detector predictions





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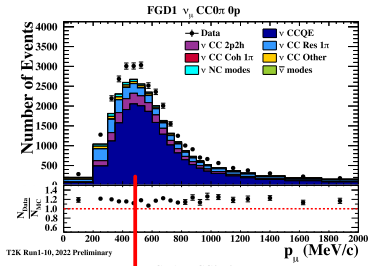
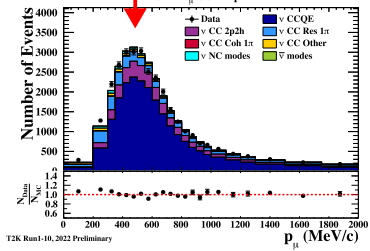
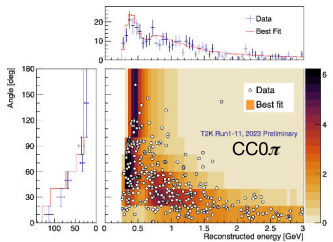
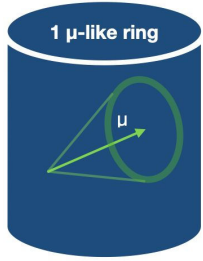




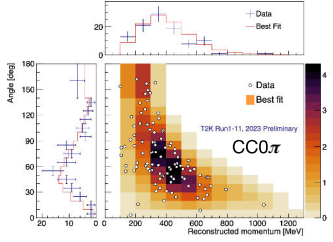
Far detector samples

Muon-like

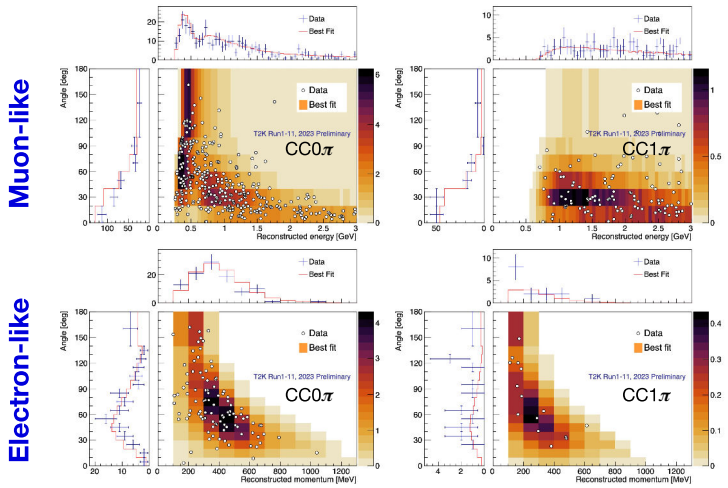


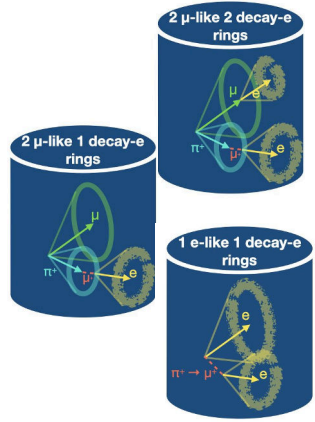


Electron-like

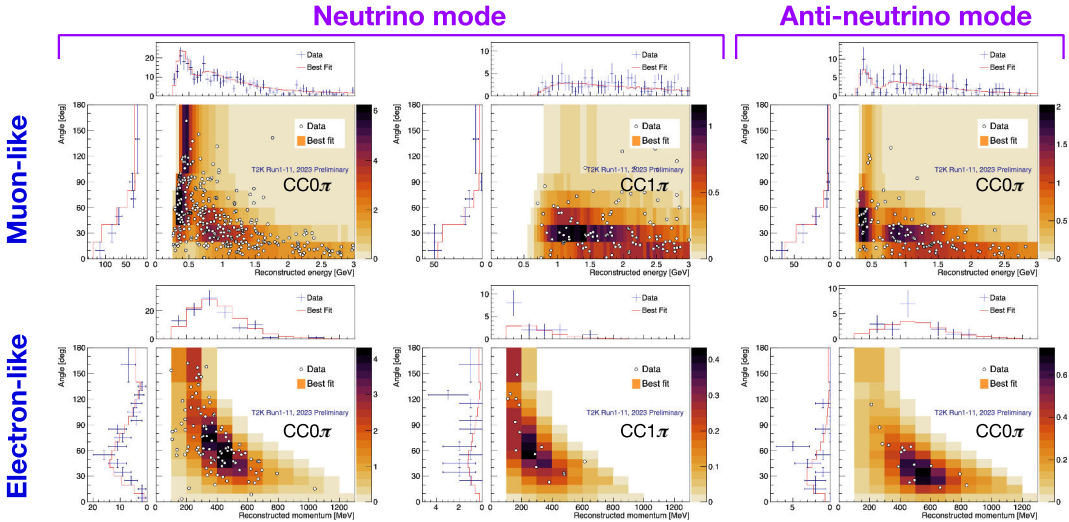


Far detector samples



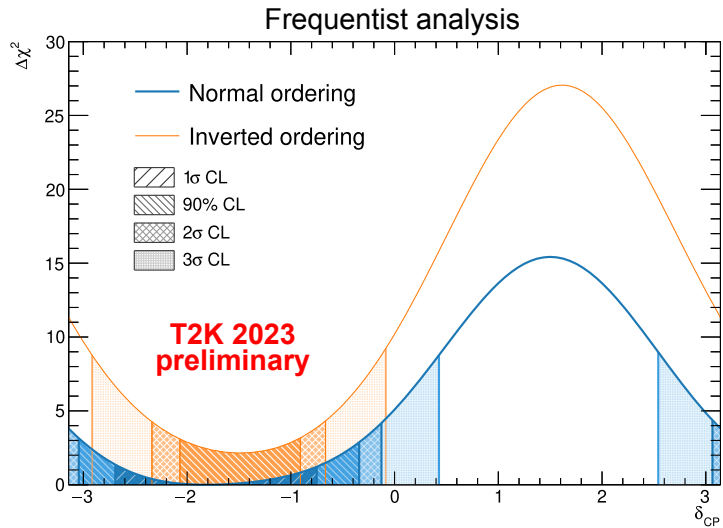


Far detector samples

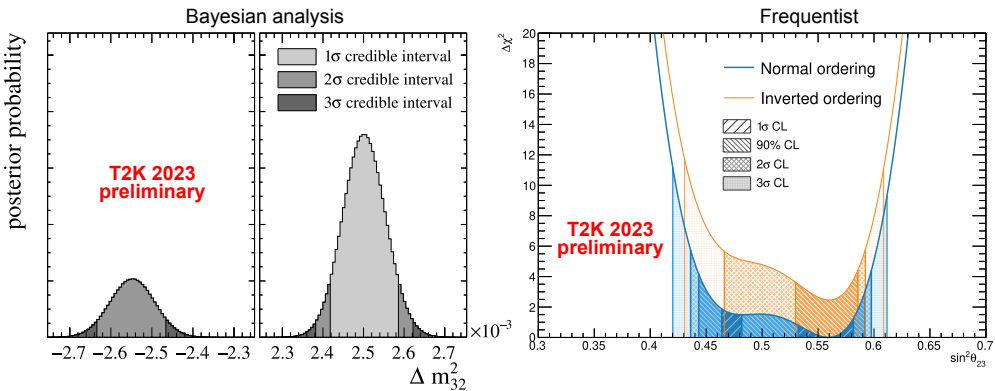


Oscillation analysis results

- CP conservation excluded with 90% C.L. regardless of mass ordering
- Best-fit value close to maximal CP violation $\delta_{\mathrm{CP}} = -\pi/2$



Oscillation analysis results

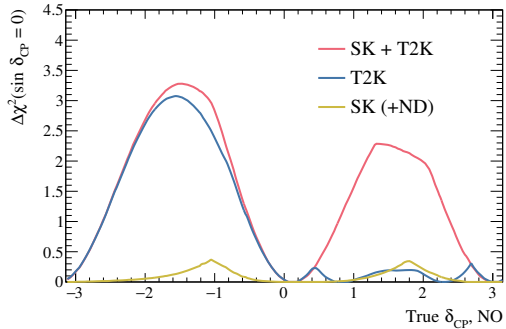


- A slight preference for both normal ordering and the upper octant of θ_{23}

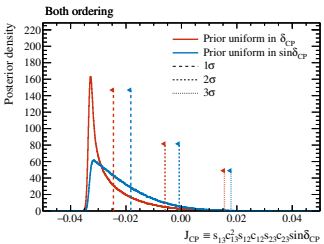
Joint analyses with SK and NOνA

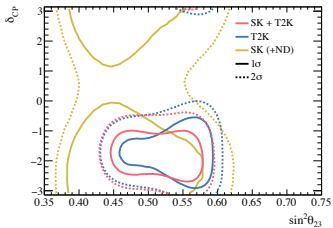
T2K+SK joint analysis

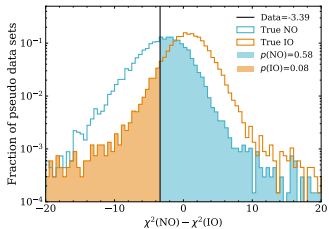
- SK atmospheric and T2K beam neutrinos have different oscillation baselines and energy ranges, but both experiments use the Super-K detector
  - Easier to unify detector model and systematic uncertainties
- T2K and SK are complementary, and the combined analysis helps lift the degeneracy:
  - T2K has good δ_{CP} sensitivity, but mild mass ordering sensitivity
  - SK has good mass ordering sensitivity, but mild δ_{CP} sensitivity



T2K+SK joint analysis

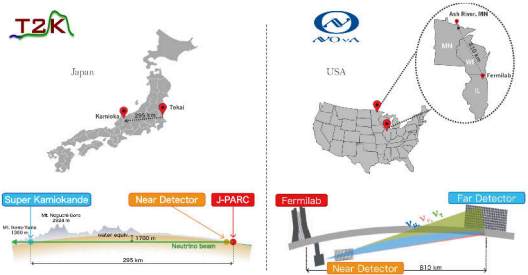






- The CP-conserving value of the Jarlskog invariant is excluded with a significance varying between 1.9σ and 2.0σ depending on the analysis considered.
- No preference for the octant of θ_{23}
- Small preference for normal mass ordering (inverted ordering excluded at 1.2σ)
- Analysis results published in Phys. Rev. Lett. 134, 011801 (2025)

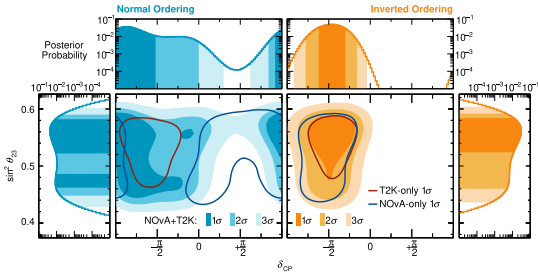
T2K-NOνA joint analysis

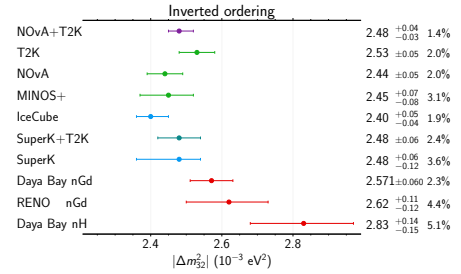


- Two complementary long baseline neutrino experiments
- T2K with better δ_{CP} sensitivity
- NOνA with better mass ordering sensitivity

	T2K	NOvA
Beam Peak Energy	0.6 GeV	2 GeV
Osc. Baseline	295 km	810 km
Detectors	Fine-Grained Scintillator (ND) and Water Cherenkov (FD)	Segmented Liquid Scintillator Bars (ND + FD)
Matter Effect	9%	29%
CP Effect	32%	22%

T2K-NOνA joint analysis



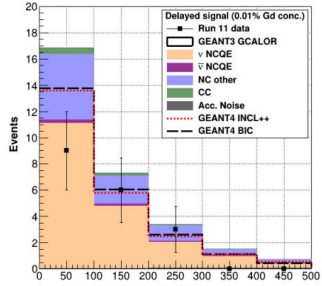


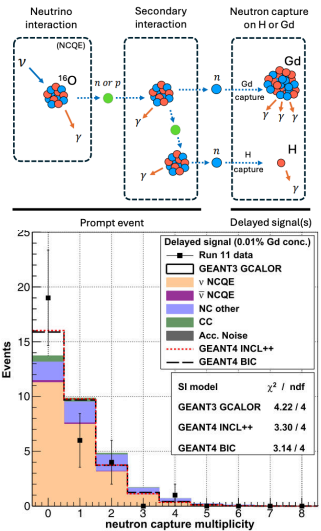
- Small preference for inverted ordering, while both experiments separately prefer normal ordering
- In the case of inverted ordering, CP conservation is excluded at the 3σ level, while for normal ordering it is inconclusive
- Most precise measurement of $|\Delta m^2_{23}|$ so far
- Results published in Nature 646, 818–824 (2025)

Latest cross-section results

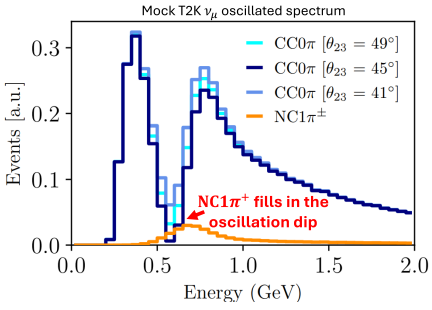
n-capture multiplicity in NCQE scattering

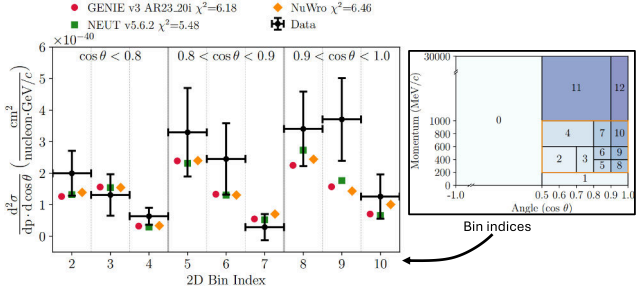
- First measurement of neutron capture multiplicity resulting from NCQE interactions on oxygen, using Super-K-Gd data.
- Significant background for diffuse supernova neutrino background searches in SK
- Neutrons identified by delayed γ emissions
- Results published in Phys. Rev. D 112, 032003 (2025)





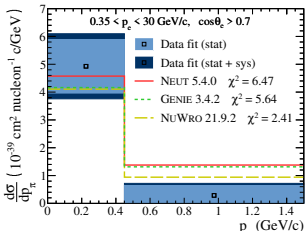
NC1π^+ on carbon

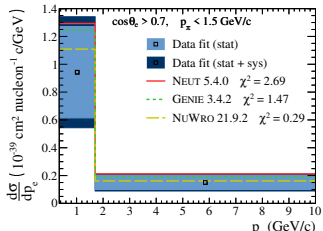


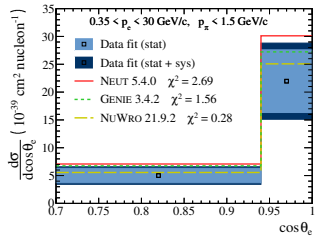


- First measurement of NC1π^+ interactions on carbon
- Important background for ν_μ disappearance measurements in T2K
- Mis-modeling limits T2K's sensitivity to θ_{23} and Δm^2_{23}
- Measurement shows that NEUT, NuWro, and GENIE under-predict the total flux-integrated cross section by $\sim 30\%$
- Results published in Phys. Rev. Lett. 135, 171803 (2025)

ν_eCCπ^+ on carbon





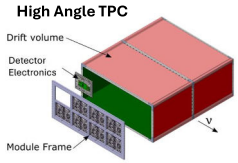


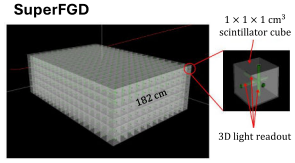
- First measurement of ν_eCCπ^+ interactions on carbon
- Important interaction in T2K ν_e appearance channel ($\sim$ 10% of statistics)
- The total flux-integrated cross-section result is lower than predictions from three neutrino generators: NEUT, NuWro, and GENIE.
- Largest discrepancy is in the 0.45 GeV/c $< p_\pi <$ 1.5 GeV/c region
- Results published in Phys. Rev. Lett. 135, 151802 (2025)

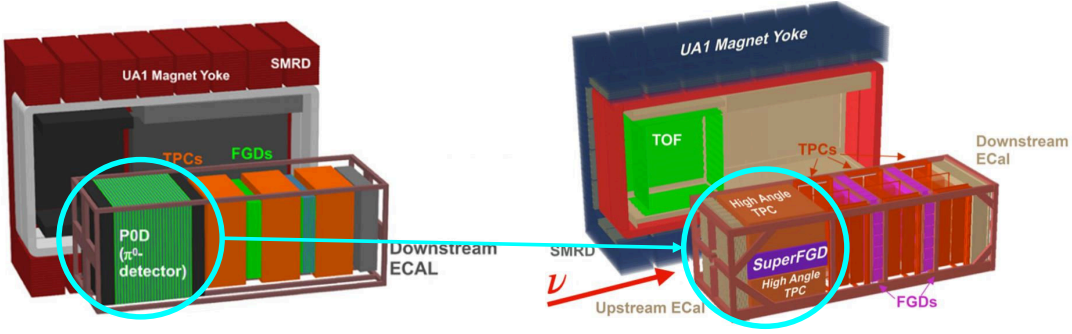
Looking into the future

ND280 upgrade

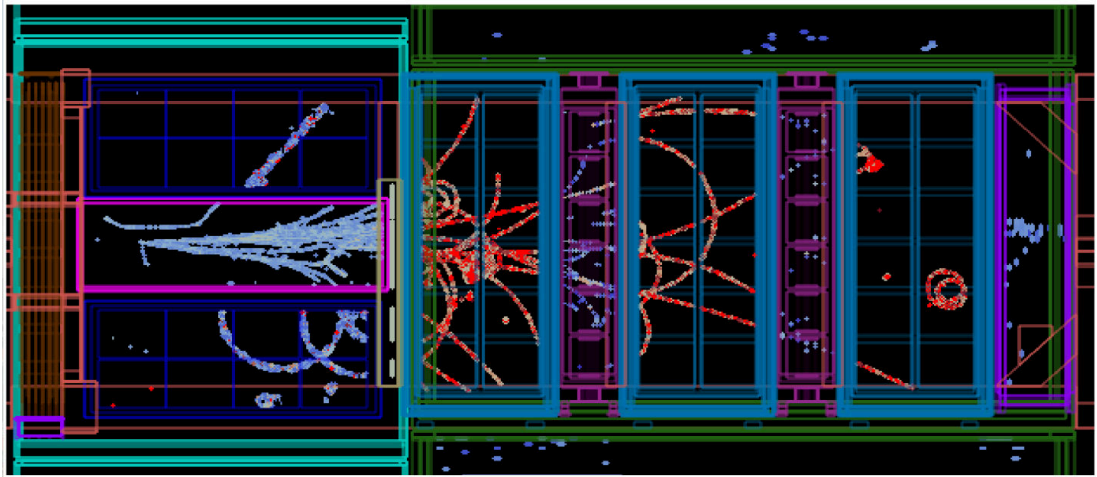
- ND280 was upgraded in 2023-2024. The first physics data were taken in June 2024
- Target detector is made of two million plastic scintillator cubes with three-directional fiber readout (SuperFGD)
- Top and bottom TPCs (high-angle TPCs) provide high acceptance, and a TOF detector identifies direction.







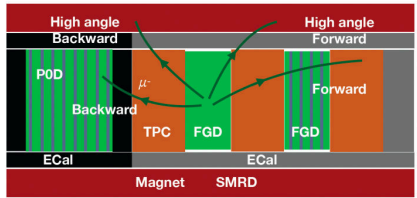
ND280 upgrade - event display

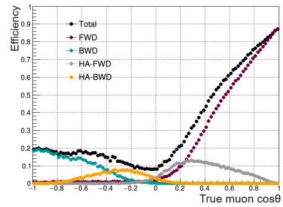


Updates in ongoing oscillation analyses

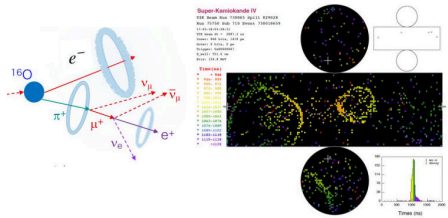
- Improved cross-section model
- New 4π selection to cover large phase space in ND280 (before hardware upgrade)
- New multi-ring sample in Super-K
- Updated SK detector systematics evaluation

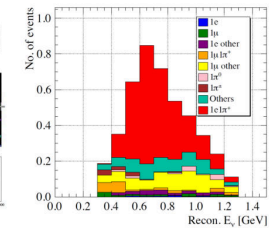
New 4π event selection in ND280





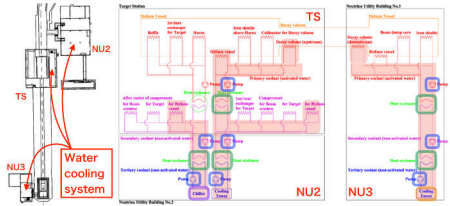
New multi-ring ν_e sample in SuperK

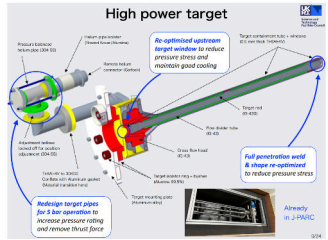


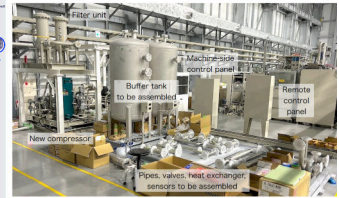


Accelerator and beamline upgrades

- Steady increase of proton beam power delivered by MR:
  - Beam power is being increased from 750 kW to 1.3 MW
  - Stable running at 900 kW in January-March 2026
  - Several 1 MW test shots
- Many upgrades to ν-beamline are coming:
  - Installation of a 1.3 MW-capable target
  - New target cooling system
  - Massive upgrade of the facility cooling, in preparation for the MW beam power era
  - Increased horn current from 250 kA to 320 kA (since 2024)







Summary

- T2K continues to deliver important results in neutrino oscillation physics and neutrino interaction measurements
- Several first-of-their-kind cross-section measurements have been performed using ND280 and Super-Kamiokande data
- First joint oscillation analyses with Super-Kamiokande atmospheric data and NOνA have recently been published
- Upgrades to the J-PARC accelerator chain and neutrino beamline will enable steadily increasing beam power and statistics
- Analyses using new ND280 and Super-Kamiokande data samples are ongoing; in addition, the statistics will increase significantly. Stay tuned for upcoming results!

Thank you.