Status of T2K and Hyper-Kamiokande

PANIC 2021

September 5, 2021

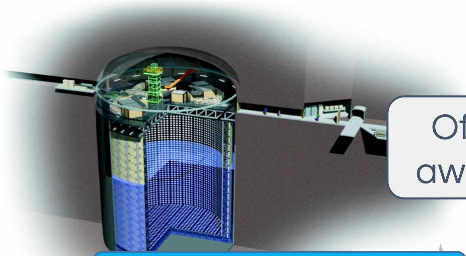
Cristóvão Vilela on behalf of the T2K Collaboration and Hyper-Kamiokande

The Tokai-to-Kamioka Experiment

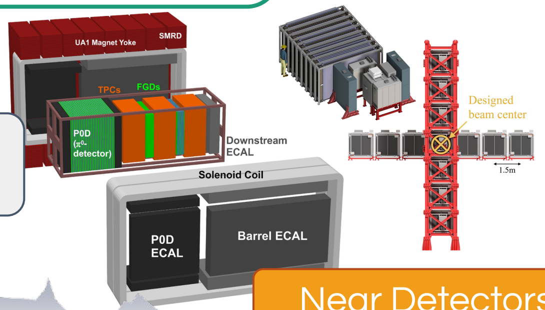
- First observation of electron-neutrino appearance in a muon beam in 2013.
  - Phys. Rev. Lett. 112, 061802 (2014)
- Strongest constraint on leptonic CP violation.
  - Nature 580, 339–344 (2020)
- World-leading precision on θ_{23} and Δm^2_{32}.
- Very active neutrino cross-section measurement program!

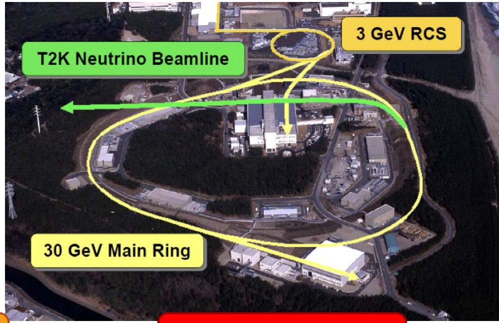
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{+i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12}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

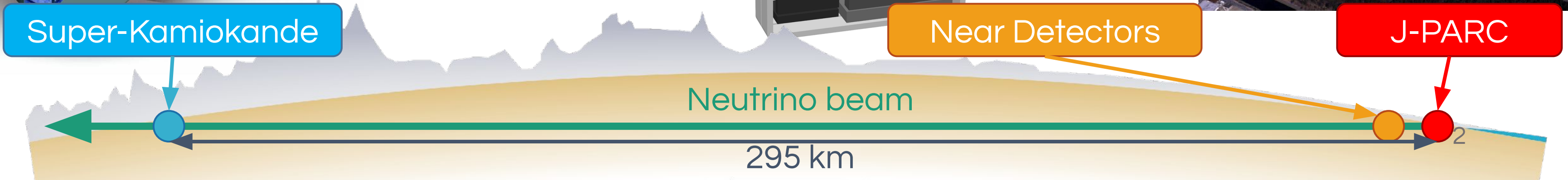
$$(L/E)^{-1}_{T2K} \approx \Delta m^2_{Atm.}$$



Off-axis detectors 2.5° away from beam center



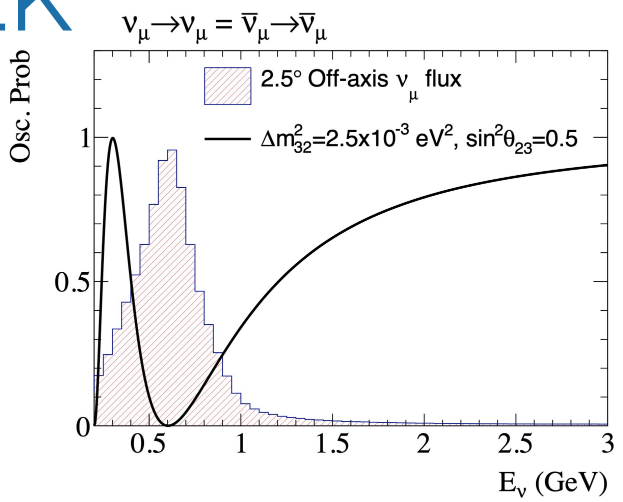




Neutrino oscillations at T2K

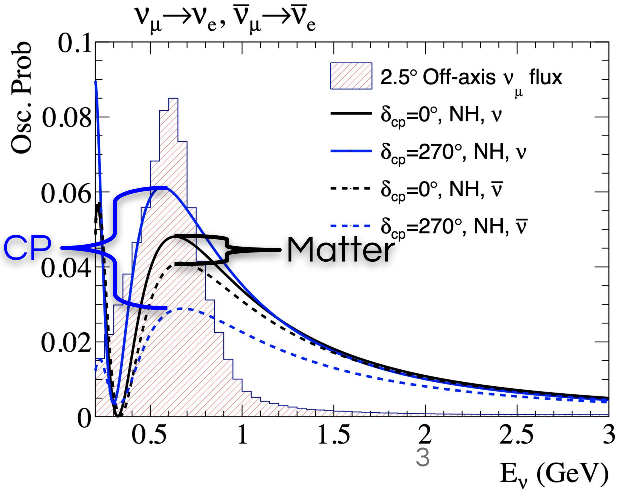
ν_μ Disappearance

- Sensitive to **$|\Delta m^2_{32}|$** and **θ_{23}**.
- Is **θ_{23}** = 45°? If not, what octant?
  - Maximal mixing might indicate underlying symmetry.
- Is $P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$?
  - This would be an indication of CPT symmetry violation.

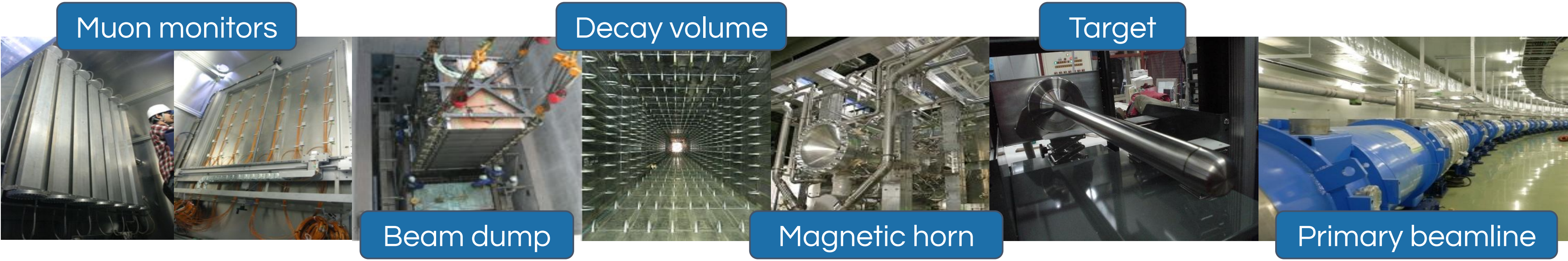


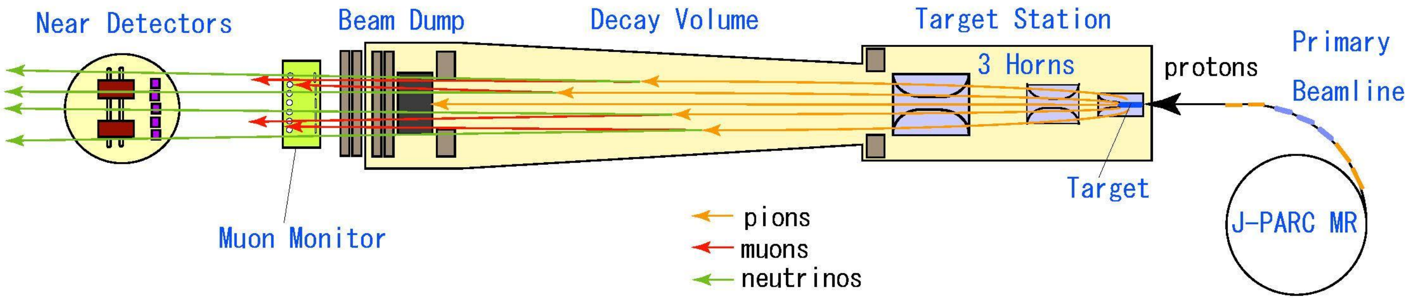
ν_e Appearance

- Sensitive to **θ_{13}, δ_{CP}, θ_{23} octant**, and mass ordering through matter effect.
- If **δ_{CP}** different from 0 or π **CP symmetry is violated** in lepton sector.
- $P(\nu_\mu \to \nu_e)$ is enhanced if mass ordering is normal or **δ_{CP}** ~ - π /2
- $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ is enhanced if mass ordering is inverted or **δ_{CP}** ~ π /2
- With the T2K flux, the matter effect (∝ L) is smaller than **δ_{CP}**.
  - Complementarity with NOvA and DUNE, with similar L/E but larger E and L.



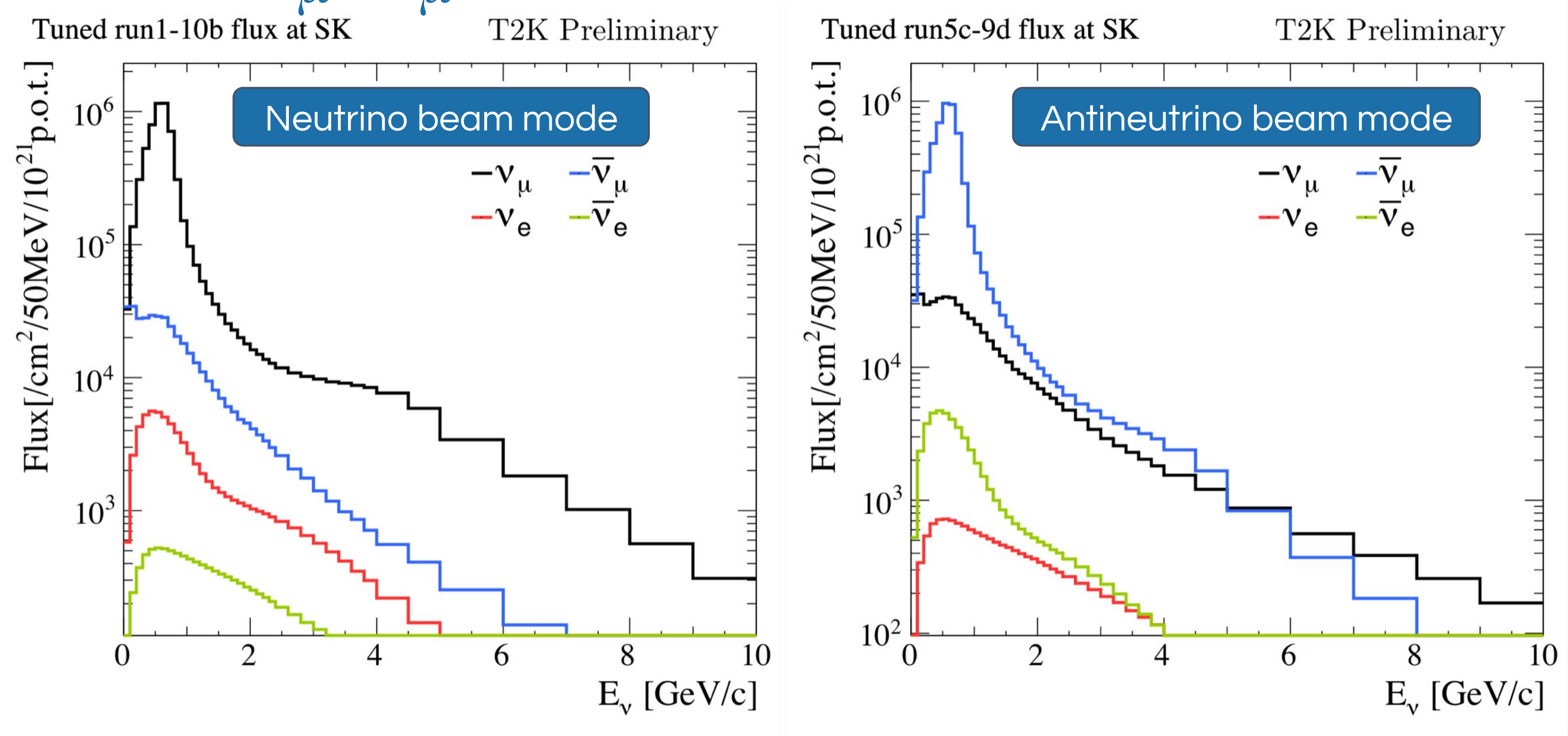
The T2K Beamline





- Protons are extracted from the 30 GeV J-PARC main ring accelerator with the superconducting primary beamline.
- $\pi^{\pm}$ are focused by three magnetic horns and allowed to decay into $\mu^{\pm}$ and ν_{μ} ($\bar{\nu}_{\mu}$)
  - Horn polarity selects charge of focused $\pi^{\pm}$, and a neutrino or antineutrino dominated beam.
- Muon detectors downstream of beam dump monitor beamline stability.

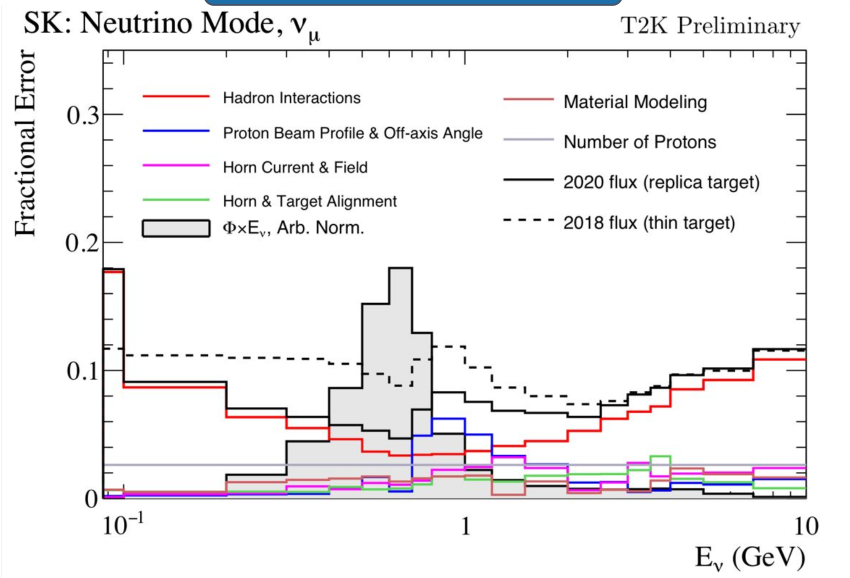
T2K ν_μ ($\bar{\nu}_\mu$) flux



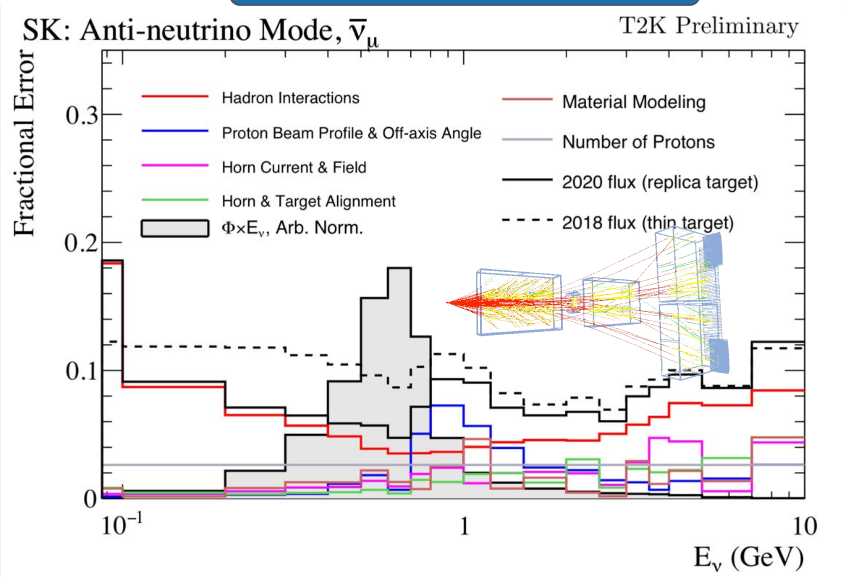
- Very low ν_e ($\bar{\nu}_e$) contamination. Less than 1% near oscillation maximum.
  - Irreducible background to ν_e ($\bar{\nu}_e$) appearance.
- Wrong sign contamination more significant in antineutrino mode.

Far detector ν_μ ($\bar{\nu}_\mu$) flux uncertainty

Neutrino beam mode



Antineutrino beam mode

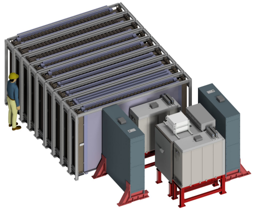


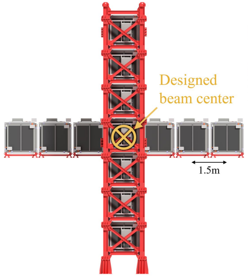
- Flux uncertainty constrained by beamline instrumentation and external measurements of hadron production at NA61/SHINE.
- Hadron production measurements using a T2K target **replica** reduced the uncertainty from ~10% to ~5% in 2020 analysis.
- In the oscillation analysis, the uncertainty gets further constrained by near detector measurements.
    - Significant cancelation in near-to-far detector extrapolation.

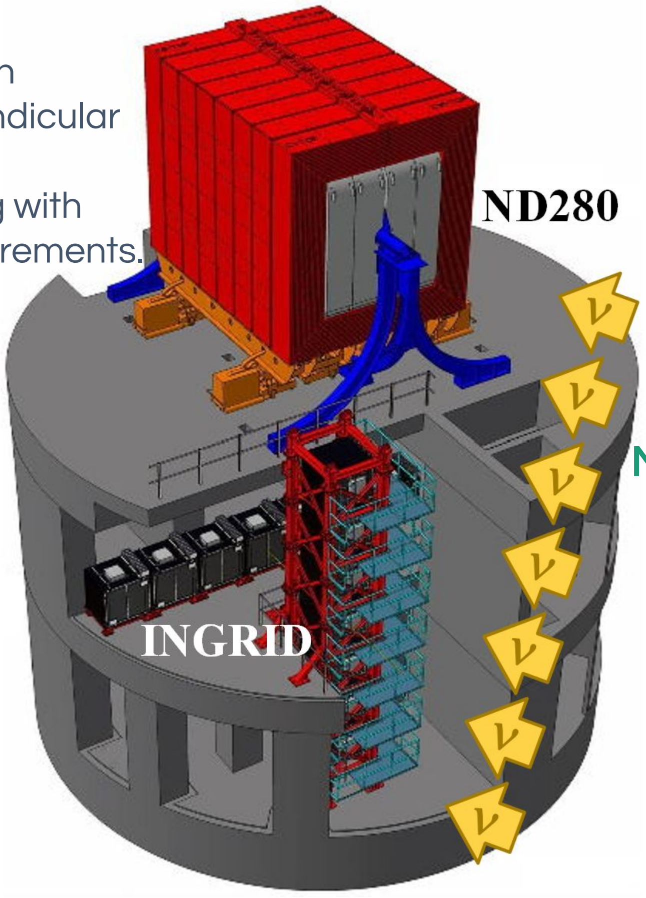
The T2K Near Detector complex

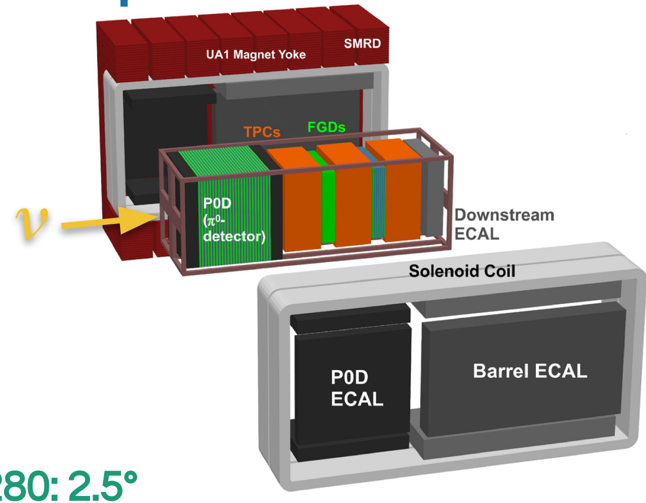
INGRID: on-axis

- Plastic scintillator and iron arranged in a grid perpendicular to the beam axis.
- Beam stability monitoring with **direction** and **rate** measurements.









WAGASCI/BabyMIND: 1.5°

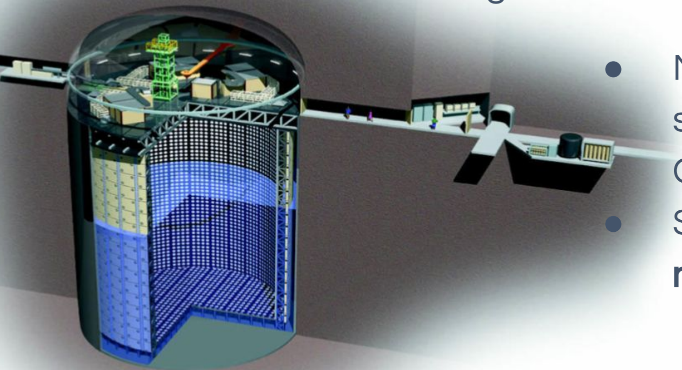
- Latest addition to ND complex!
- Water target in plastic scintillator lattice.
- Magnetized iron spectrometer.

ND280: 2.5°

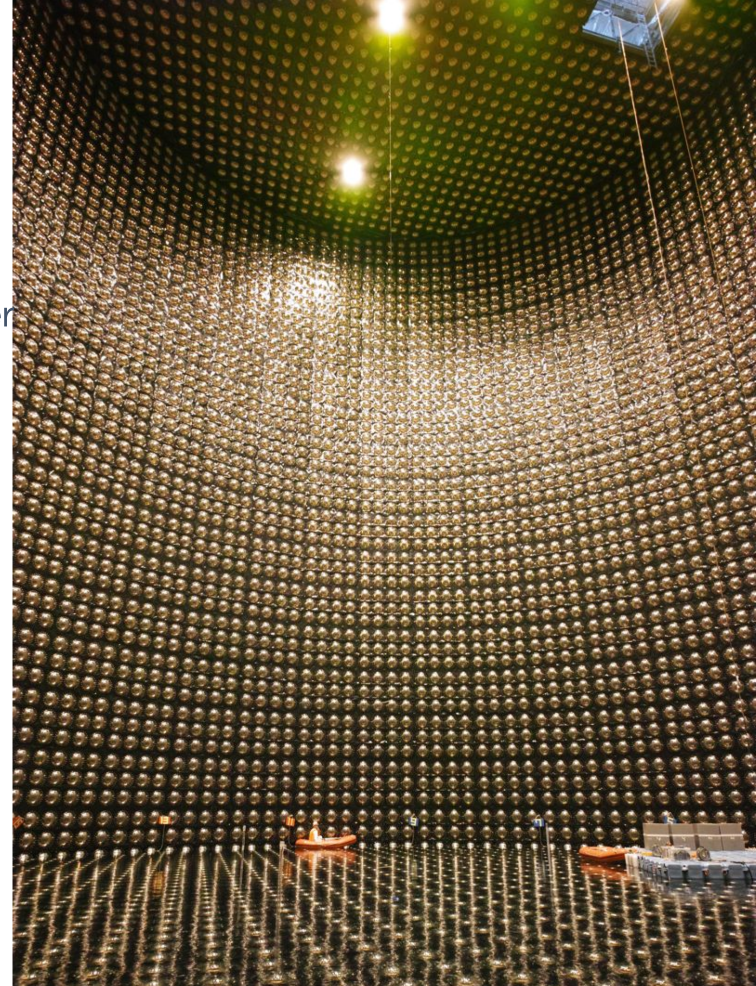
- Detectors in 0.2T field generated by repurposed UA1/NOMAD magnet.
  - $\nu_\mu/\bar{\nu}_\mu$ separation.
- Dedicated π^0 detector.
- Tracker composed of two plastic scintillator fine-grained detectors (FGDs) and three time projection chambers (TPCs).
- Plastic and **water** targets.

Super-Kamiokande

- 50 kilo-ton water Cherenkov detector.
- Optically separated outer detector for tagging entering/escaping particles.
- ~11000 20" photomultiplier tubes (PMTs) facing the inner detector.
  - 40% of inner surface covered by photocathodes.
- ~2000 8" PMTs in the outer detector.
- Measure momentum and direction of particles above the Cherenkov threshold.
  - Excellent μ/e separation.
  - No charge selection.

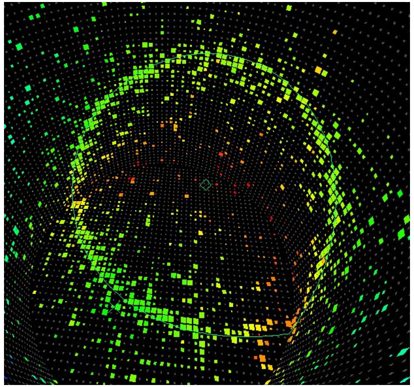


- New phase of the experiment started recently with 0.02% of Gd dissolved in the water.
- Significantly enhanced **neutron** detection capability.

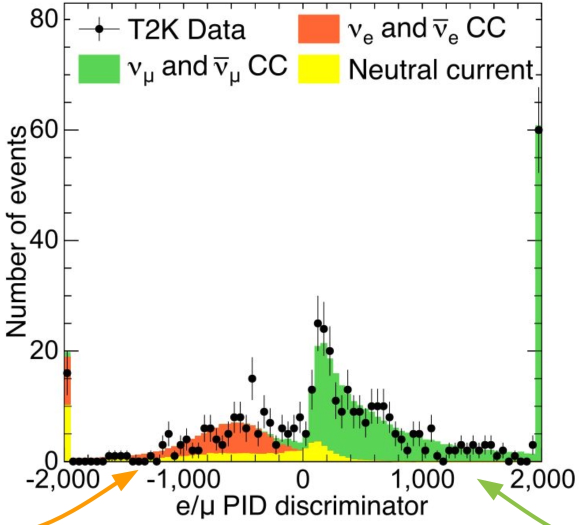


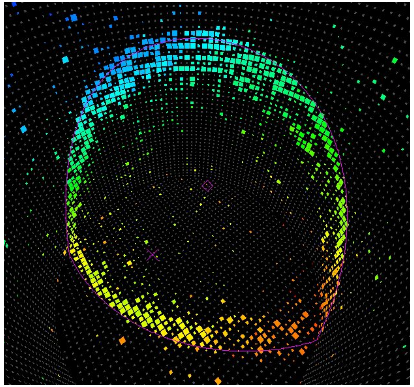
Kamioka Observatory, ICRR (Institute for Cosmic Ray Research) The University of Tokyo.

Super-Kamiokande samples



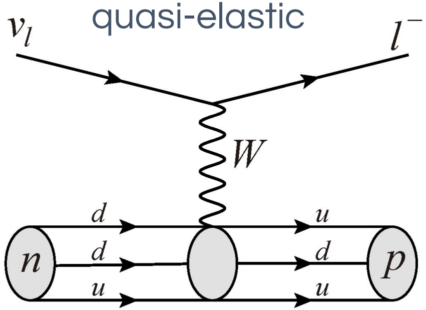
e-like ring

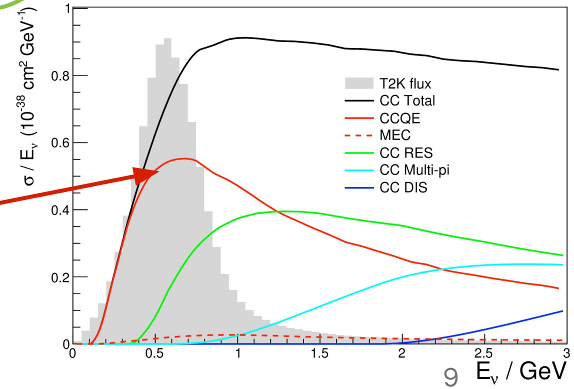




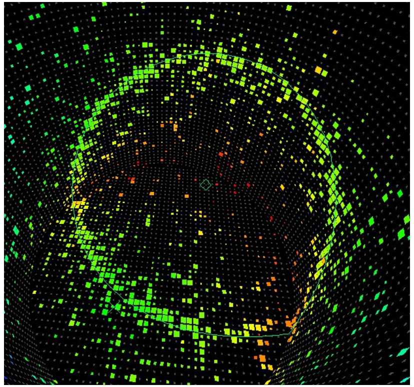
μ-like ring

- Hadronic system typically below Cherenkov threshold.
- Signal samples use single-ring event topologies.
- Infer neutrino energy from lepton momentum and θ_{beam}.

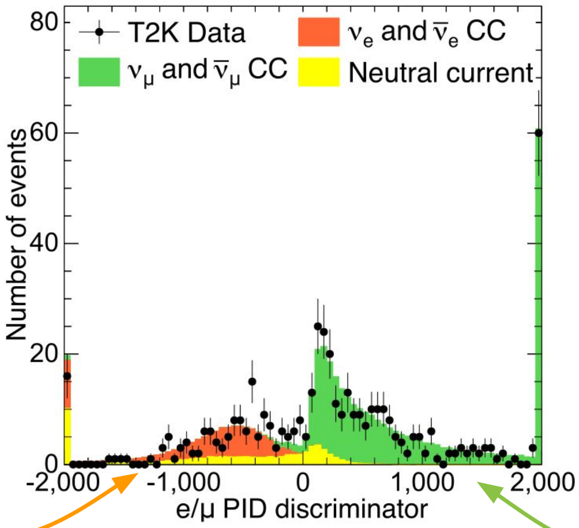


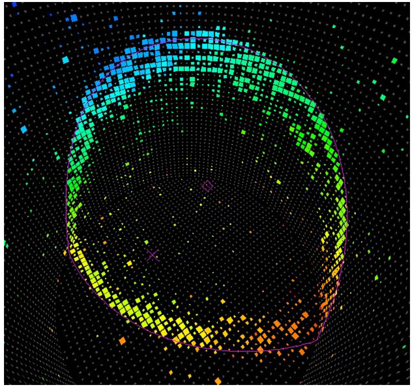


Super-Kamiokande samples



e-like ring

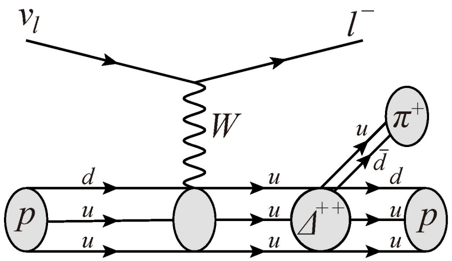


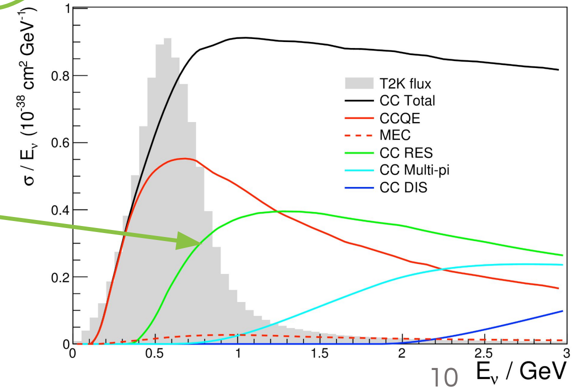


μ-like ring

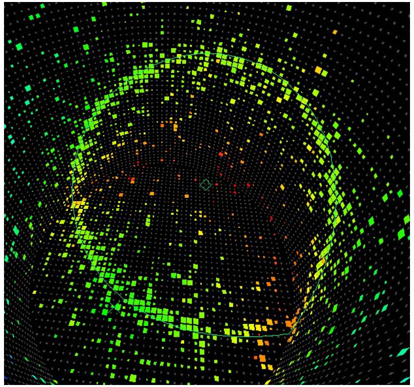
- Sample targeting resonant interactions where the final-state π^+ is below Cherenkov threshold.
- Infer the π^+ by the detection of one decay-electron.
- Used only in neutrino mode and for e-like events.

Charged-current Δ and other resonances

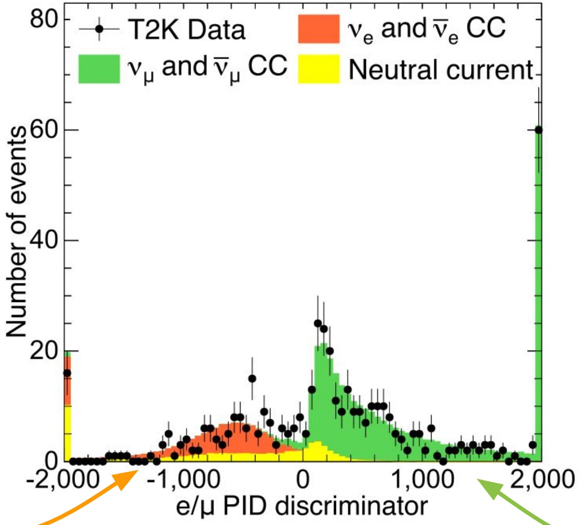


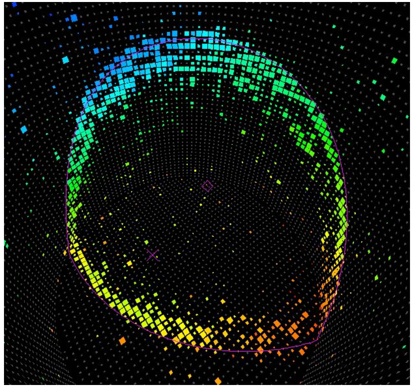


Super-Kamiokande samples



e-like ring



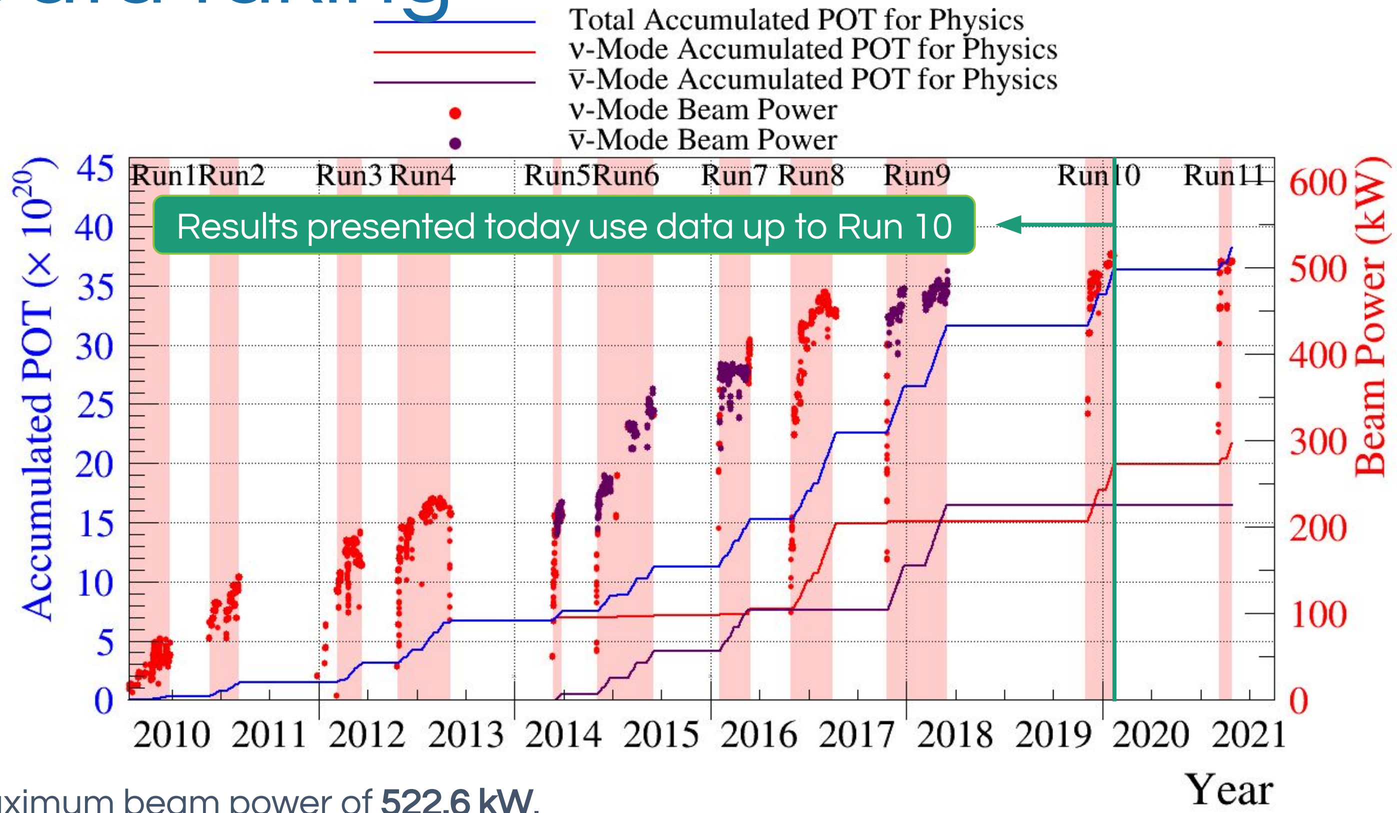


μ-like ring

- Five samples at Super-Kamiokande, targeting:
  - Charged-current quasi-elastic interactions.
  - Charged-current resonant π production.
    - π below Cherenkov threshold.
- Main backgrounds are from neutral-current π production.
  - $\pi^0 \rightarrow \gamma\gamma$ misidentified as an electron.
  - π^+ misidentified as a μ.

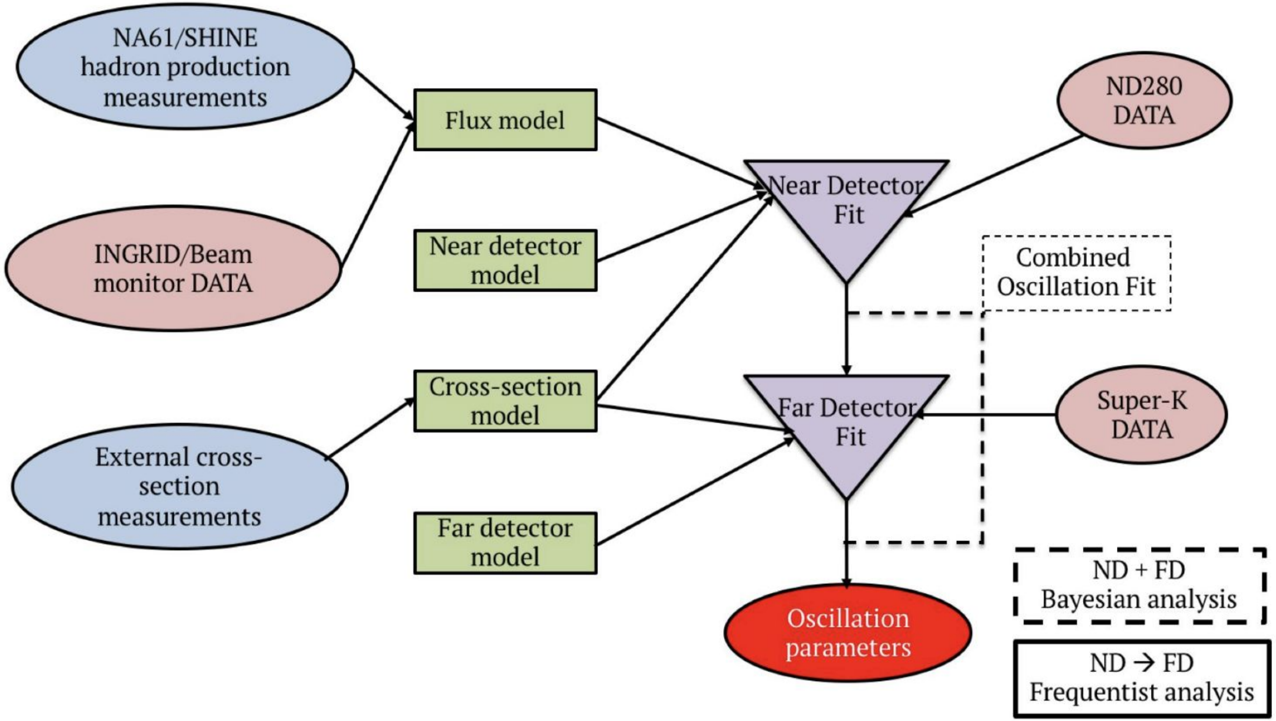
Neutrino mode	Antineutrino mode
μ-like, ≤ 1 decay-e	μ-like, ≤ 1 decay-e
e-like, 0 decay-e	e-like, 0 decay-e
e-like, 1 decay-e	

Data taking



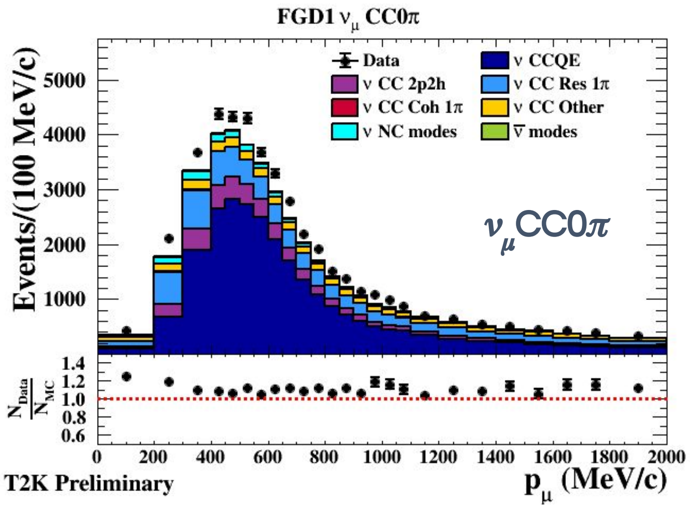
- Maximum beam power of **522.6 kW**.
- 3.6 x 10^{21} POT collected up to Run 10, 55% in neutrino mode and 45% in antineutrino mode.
- Analysis of Run 11 data is ongoing: 1.8 x 10^{20} POT collected with Gd-loaded far detector.

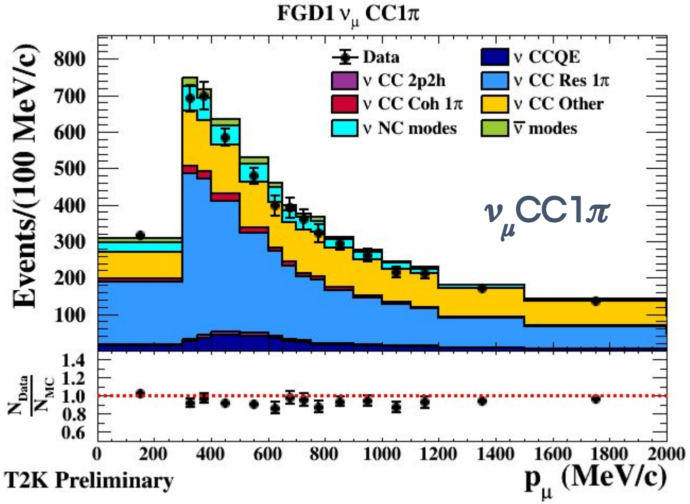
Oscillation analysis strategy



Near detector fit

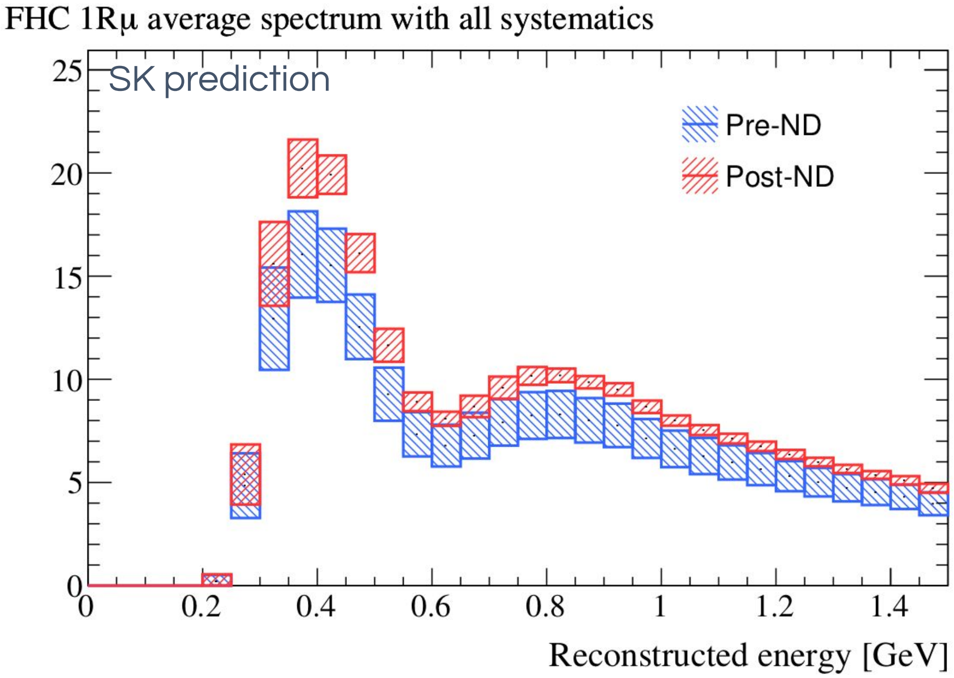
- New near detector event selection since 2020.
- Select events into **18 samples** according to:
  - Number of reconstructed π.
    - ν_μ**CC0**π, ν_μ**CC1**π and ν_μ**CCN**π.
  - Vertex in **water + carbon** and **carbon-only** targets.
  - Sign of μ track.
    - **Neutrinos** (μ^-) in neutrino mode.
    - **Neutrinos** (μ^-) and **antineutrinos** (μ^+) in antineutrino mode.
- Fit samples in μ momentum and θ_{beam}.
- Double near detector data used compared to previous analysis.
- Improved interaction model, such as:
  - Better description of nucleus initial state.
  - Better treatment of removal energy.
- Pre-fit model p-value of 74%.

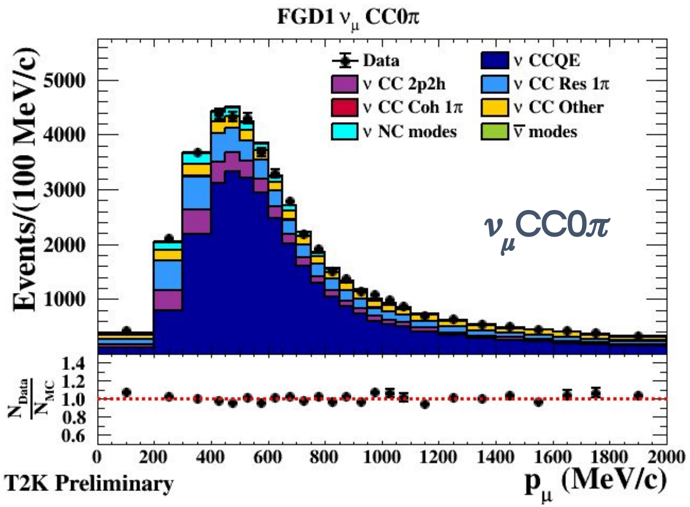


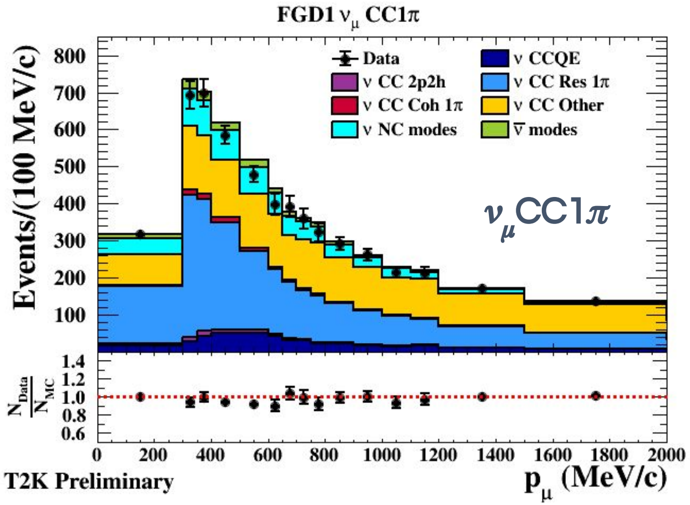


Near detector fit

- After the near detector fit, the uncertainty on the far detector prediction is reduced to around ⅓ of the pre-ND-fit value.

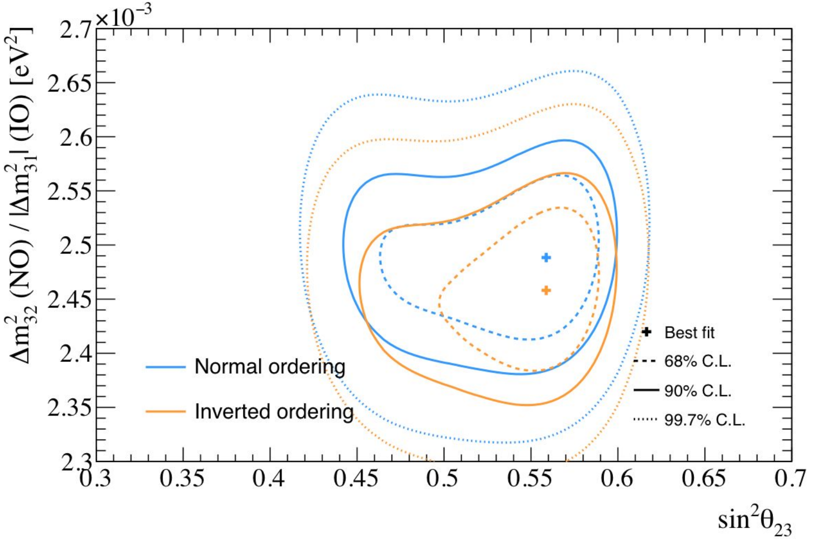




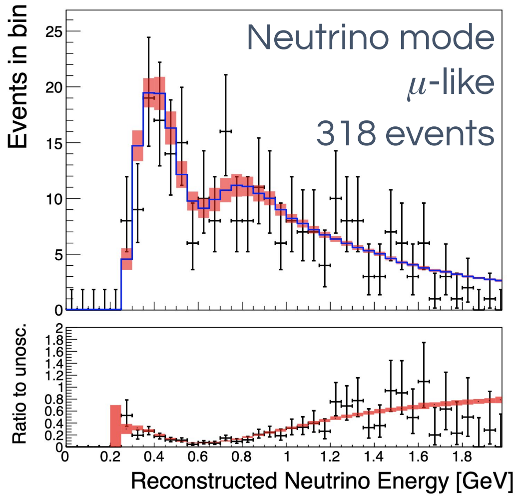


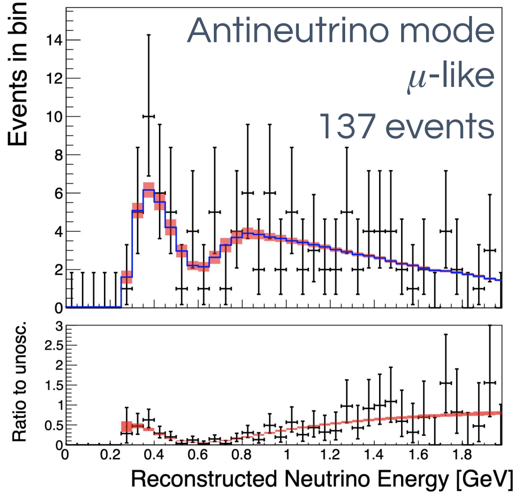
Atmospheric sector

- T2K data shows a weak preference for the **upper** octant and for the **normal** mass ordering.



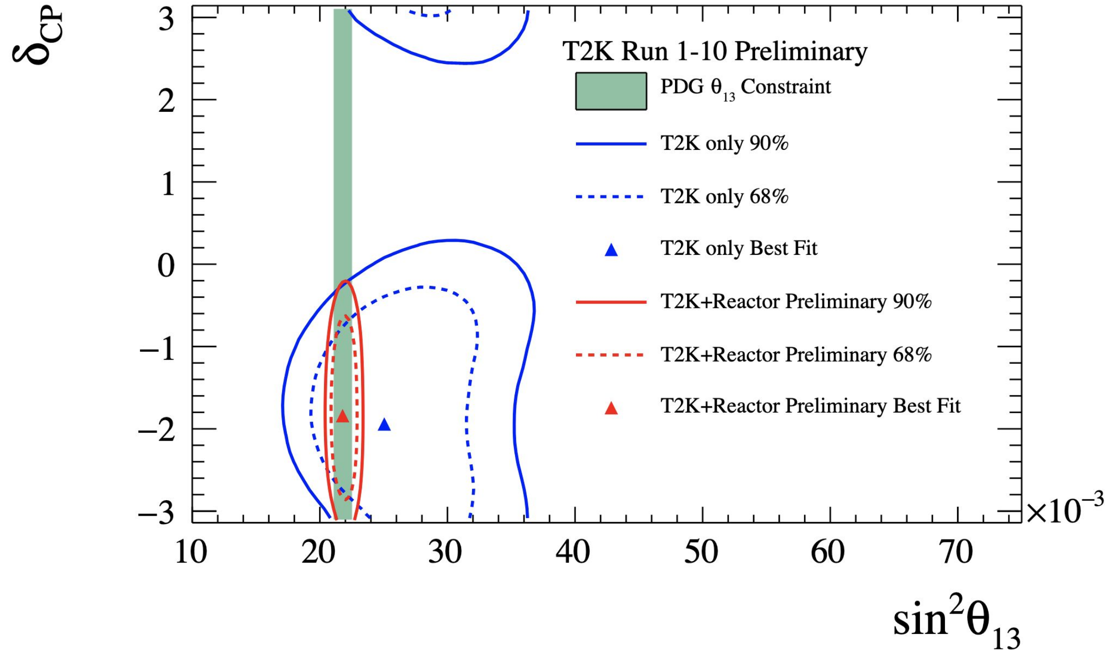
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IO ($\Delta m^2_{32} < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

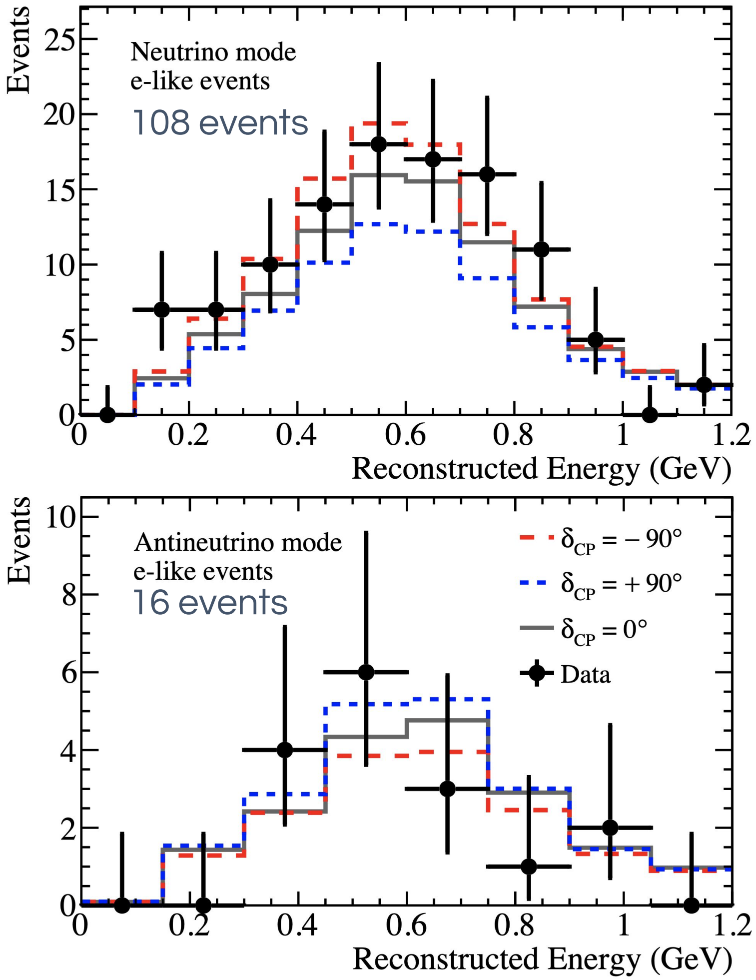




δ_{CP} constraint

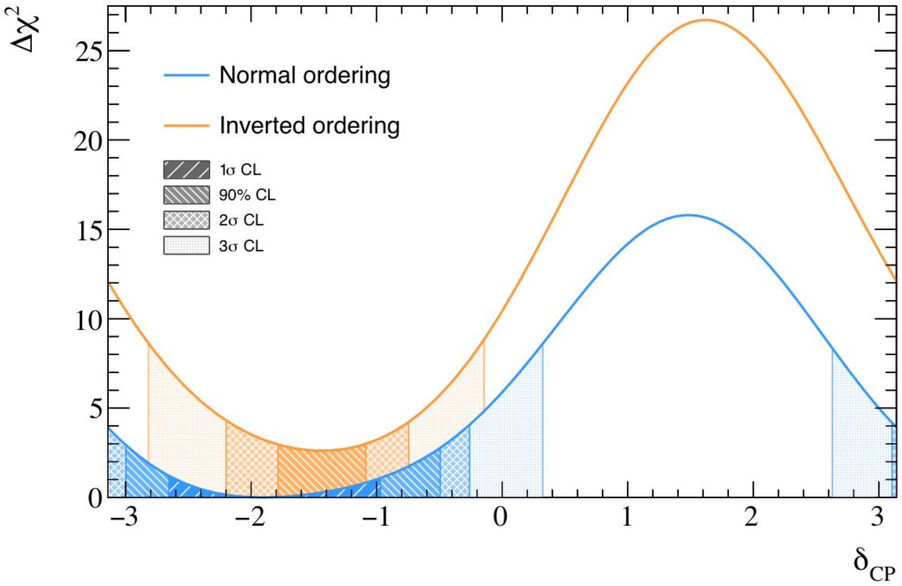
- Our results are in good agreement with the reactor experiment measurements of θ_{13}.
- The T2K data **by itself** excludes some values of δ_{CP} at 90% confidence level.
- The best-fit value of δ_{CP} close to $-\pi/2$.

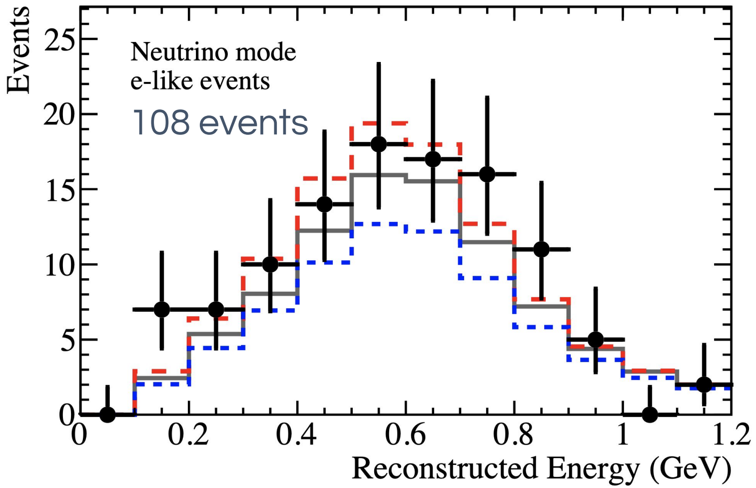


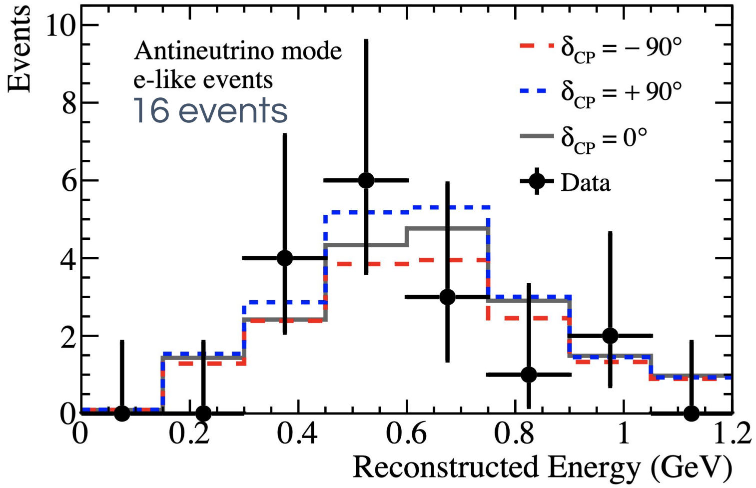


δ_{CP} constraint

- When combined with reactor experiment measurements, T2K **excludes** CP conserving values of δ_{CP} at **90%** CL.
- Marginalizing over both mass orderings, 35% of the parameter space is excluded at **3σ**.







Not just oscillations!

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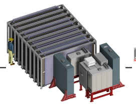
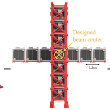
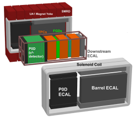




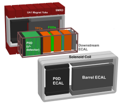
Measurements of $\bar{\nu}_\mu$ and $\bar{\nu}_\mu + \nu_\mu$ charged-current cross-sections without detected pions or protons on water and hydrocarbon at a mean anti-neutrino energy of 0.86 GeV

PHYSICAL REVIEW D **103,** 112009 (2021)



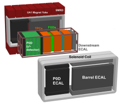
First T2K measurement of transverse kinematic imbalance in the muon-neutrino charged-current single-π^+ production channel containing at least one proton

PHYSICAL REVIEW D **102,** 012007 (2020)



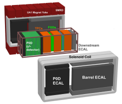
First measurement of the charged current $\bar{\nu}_\mu$ double differential cross section on a water target without pions in the final state

PHYSICAL REVIEW D **101,** 112004 (2020)



Simultaneous measurement of the muon neutrino charged-current cross section on oxygen and carbon without pions in the final state at T2K

PHYSICAL REVIEW D **101,** 112001 (2020)



First combined measurement of the muon neutrino and antineutrino charged-current cross section without pions in the final state at T2K

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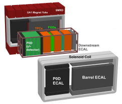
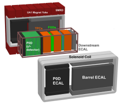


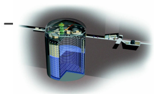
Measurement of the charged-current electron (anti-)neutrino inclusive cross-sections at the T2K off-axis near detector ND280

PHYSICAL REVIEW D **101,** 012007 (2020)



Measurement of the muon neutrino charged-current single π^+ production on hydrocarbon using the T2K off-axis near detector ND280

PHYSICAL REVIEW D **100,** 112009 (2019)

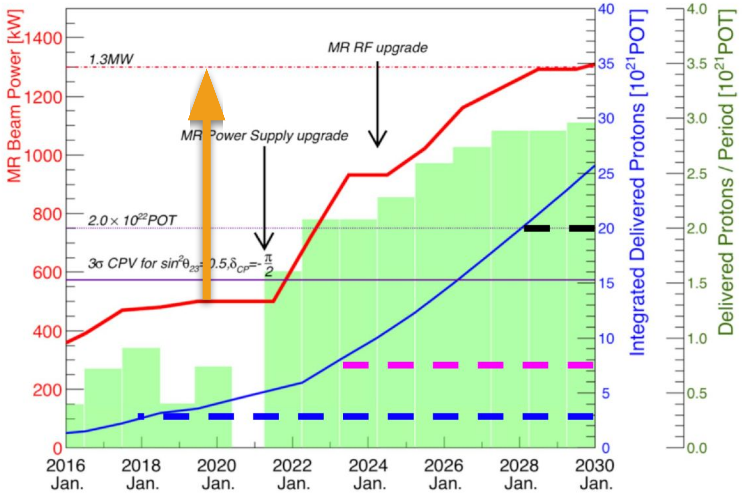


Measurement of neutrino and antineutrino neutral-current quasielasticlike interactions on oxygen by detecting nuclear deexcitation γ rays

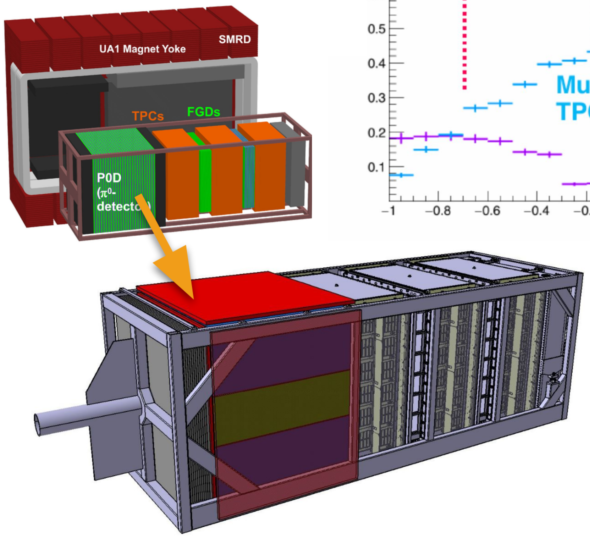
The future of T2K

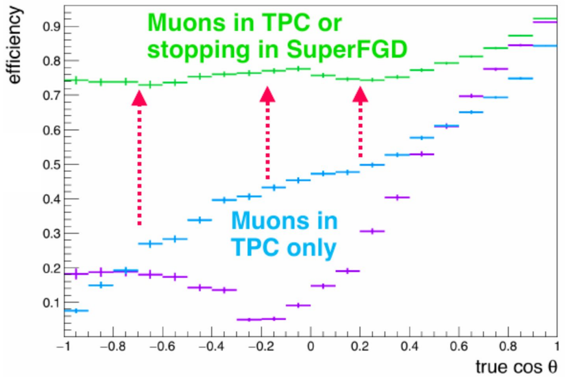
- The current T2K results hint at **large CP violation** in neutrino oscillations.
  - There may be an opportunity for T2K to achieve **3σ** evidence for CP violation!
- T2K was recently **approved** to run until the start of the next-generation experiment, Hyper-Kamiokande, expected to start in **2027**.
- Extended run of T2K matched with **two major upgrades** which are ongoing.

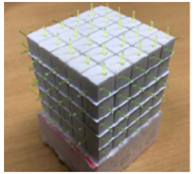
Double repetition rate of J-PARC Main Ring



Near detector upgrade

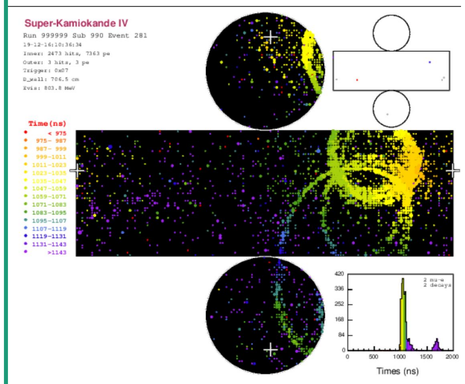


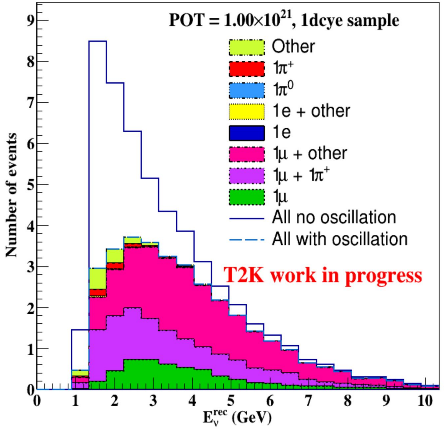


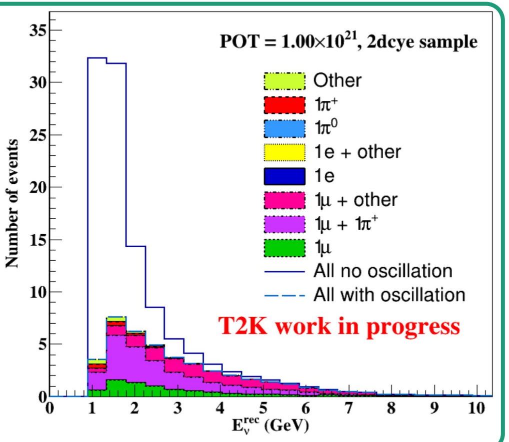


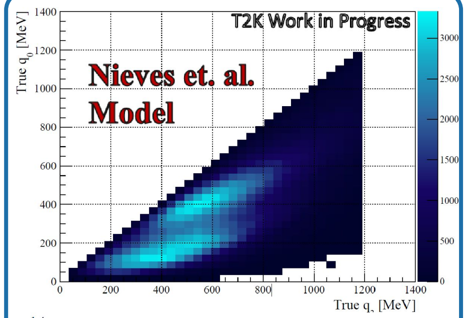
Upcoming analysis updates

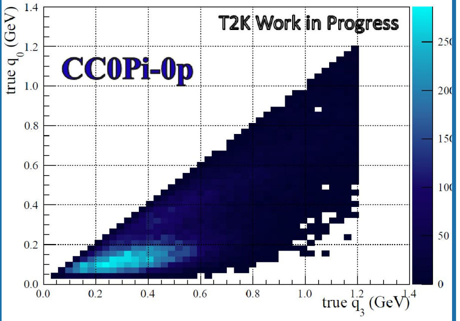
- New samples at the **far detector**, targeting resonant interactions with multiple resolved primary particles.
  - Start with **two-ring** $1\mu 1\pi+$ sample, expect 20% more statistics.
- New samples at the **near detector** separated by proton multiplicity.
  - Powerful probe of nuclear models.
- And many more updates...

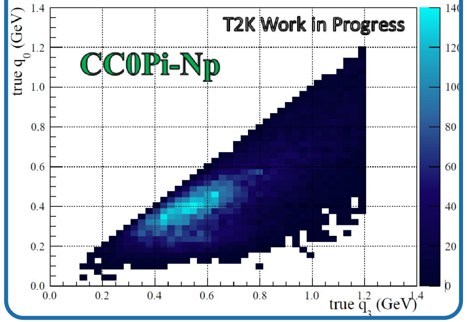








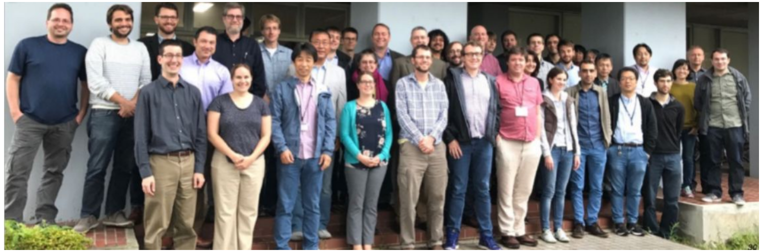




Combined analyses with SK and NOvA

- T2K has significant complementarity with **NOvA** and the **Super-Kamiokande atmospheric** neutrino sample.
  - In particular, NOvA and atmospheric neutrinos have higher energies and are therefore more sensitive to the matter effect, and the neutrino mass ordering.
- Agreements signed with both collaborations and efforts towards combined **T2K+SK** and **T2K+NOvA** analyses are now underway.
- Combined analyses will resolve degeneracies: expect significantly improved constraints on oscillation parameters!

T2K-NOvA meetings



J-PARC, Japan

Fermilab, USA

Hyper-Kamiokande

The Hyper-Kamiokande Experiment

- Hyper-Kamiokande is a next-generation water Cherenkov experiment.
  - Located in Kamioka, close to Super-K.
- Like Super-K, the detector is a large cylinder filled with water but it will be **much larger**:
  - 68 m in diameter and 71 m tall.
  - 258 kilo-ton of water (~8 x Super-K fiducial volume).
- Instrumented with:
  - 20" PMTs with significantly improved photon detection efficiency.
    - Funding for 20000 20" PMTs has been secured.
  - Multi-PMT assemblies consisting of several 3" PMTs
  - 3" PMTs equipped with wavelength-shifting plates in outer detector.
- Construction **started** in 2020!
- Expect first data in **2027**.

Ground broken!

Start of access tunnel excavation

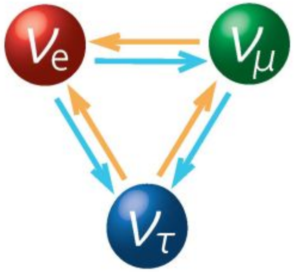
Recent status of access tunnel

High-efficiency Hyper-K PMTs

Hyper-Kamiokande Physics

- Hyper-Kamiokande will have a multifaceted Physics program.

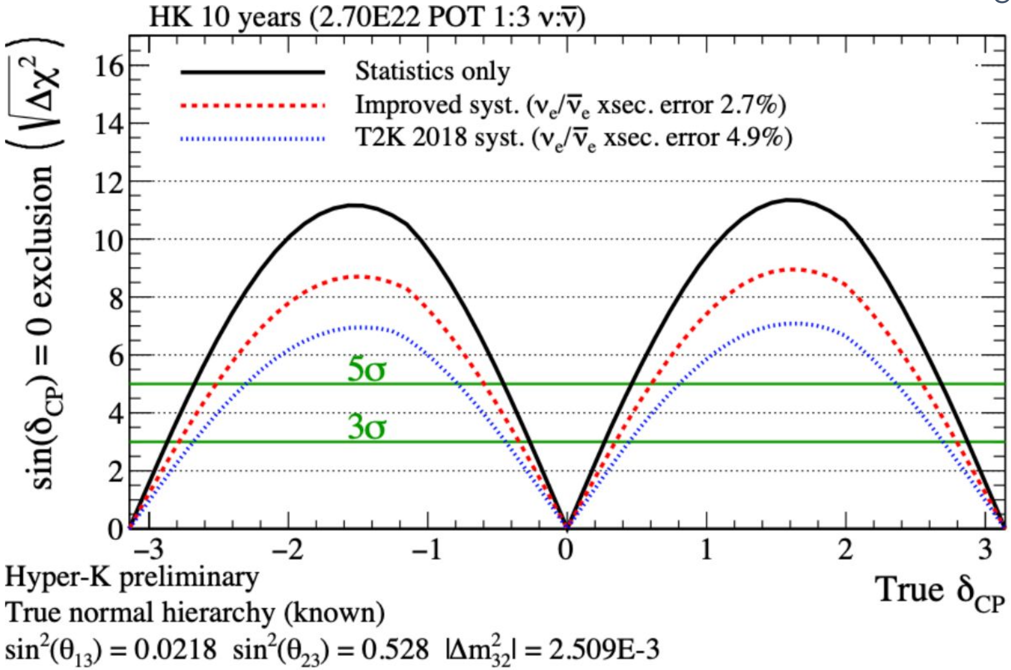
Neutrino oscillations	Neutrino astronomy	Nucleon decay
• Measure neutrino oscillations with **accelerator** and **atmospheric** neutrinos.	• **Solar** neutrino measurements. • Search for **supernova relic** neutrinos. • Very large neutrino data set if nearby **supernova** occurs.	• Expand on Super-K's legacy with much more powerful searches for **proton decay** and other baryon number violating processes.



- Also indirect dark matter searches and many other analyses.

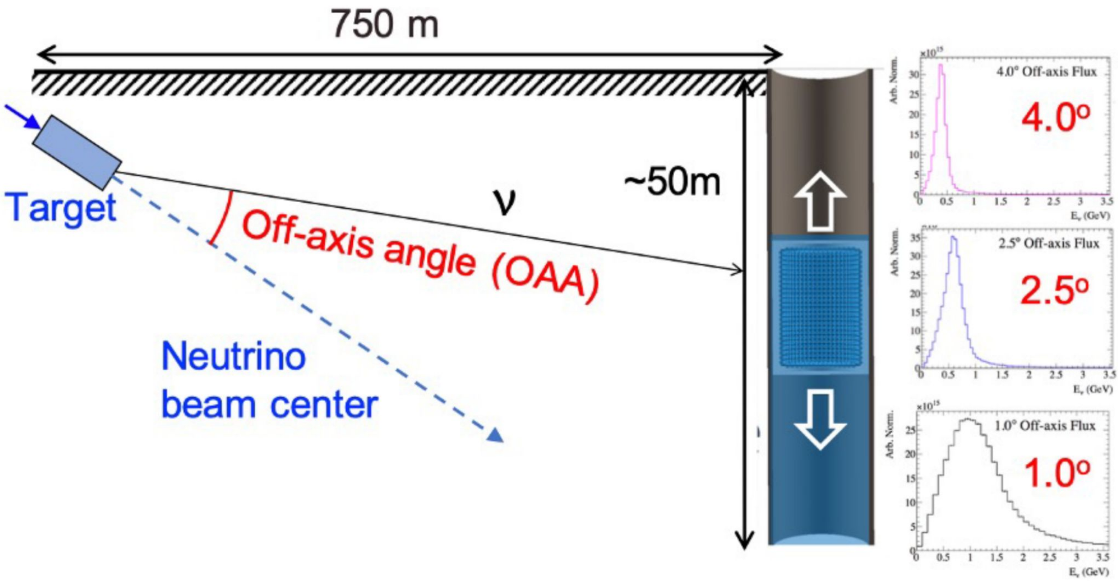
Oscillations at Hyper-Kamiokande

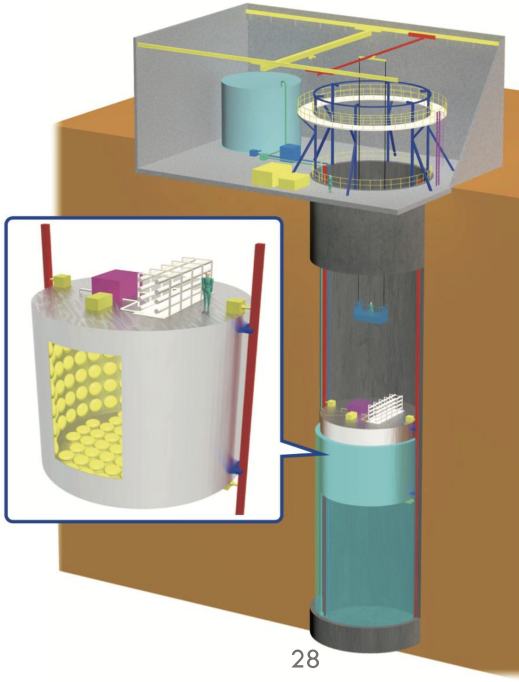
- Hyper-Kamiokande will operate on the same beamline and off-axis angle as T2K.
  - Makes use of **upgrades** to J-PARC Main Ring **accelerator** and T2K **near detector** infrastructure.
- Sensitivity to CP violation greatly improved by larger target mass and high-power beam.
- Potential for **5σ** CP violation **discovery** for a wide range of possible δ_{CP} values.



Intermediate water Cherenkov detector

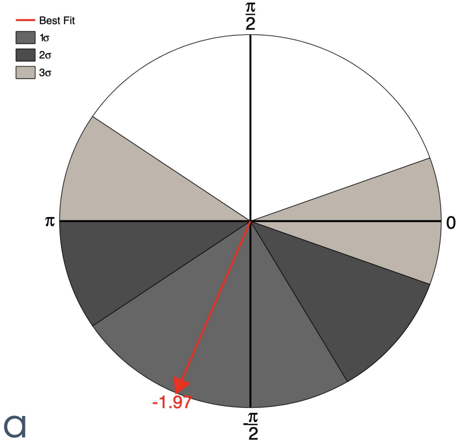
- New intermediate water Cherenkov near detector capable of making measurements at several off-axis positions.
- This detector will enable largely **data-driven** CP violation search which will mitigate the impact of interaction model uncertainties.





Summary

- The T2K data is starting to constrain CP violation in the lepton sector.
  - Exciting prospects for **CP violation evidence** within current generation of experiments.
  - **Accelerator** and **detector upgrades** underway, as well as **analysis improvements** and **combined analysis** efforts.
- **Construction has started** for Hyper-Kamiokande, the next instalment in a series of ground-breaking water Cherenkov experiments at Kamioka.



Supplementary slides

T2K Systematic uncertainties

Error source	1Rμ FHC	1Rμ RHC	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
2p2h Edep	0.4	0.4	0.2	0.2	0.0	0.2
$\mathrm{BG}_A^{\mathrm{RES}}$ low-p_π	0.4	2.5	0.1	2.2	0.1	2.1
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.7	3.0
NC γ	0.0	0.0	1.4	2.4	0.0	1.0
NC Other	0.2	0.2	0.2	0.4	0.8	0.2
SK	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

What changed since 2018?