



Status and plans for T2K neutrino oscillation analyses

Helen O’Keeffe (Lancaster University)

On behalf of the T2K collaboration.

NuFact 2025: The 26th International Workshop on Neutrinos from Accelerators

4th September 2025

Neutrino Oscillations

Values quoted from 2025 PDG (<https://pdg.lbl.gov/>)

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

Atmospheric + Accelerator

$$\sin^2 \theta_{23} = 0.537 \pm 0.020 \text{ (IO)}$$

$$\sin^2 \theta_{23} = 0.534^{+0.015}_{-0.019} \text{ (NO)}$$

$$\Delta m_{32}^2 = (-2.527 \pm 0.034) \times 10^{-3} \text{ eV}^2 \text{ (IO)}$$

$$\Delta m_{32}^2 = (2.451 \pm 0.026) \times 10^{-3} \text{ eV}^2 \text{ (NO)}$$

Reactor + Accelerator

$$\sin^2 \theta_{13} = (2.16 \pm 0.06) \times 10^{-2}$$

Accelerator

$$\delta_{CP} = 1.21^{+0.19}_{-0.22} \pi \text{ rad}$$

Solar

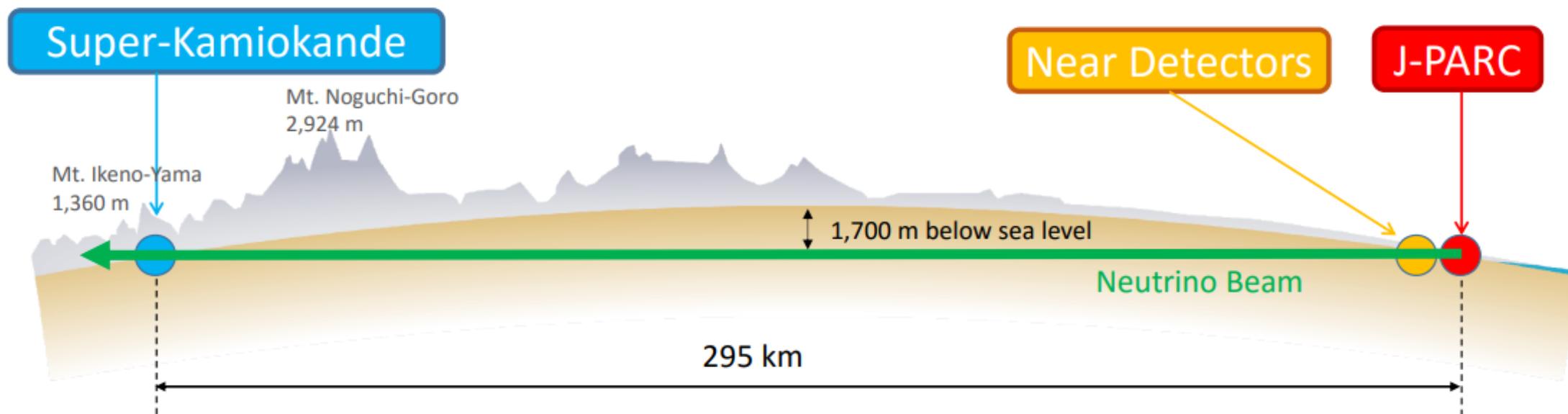
$$\sin^2 \theta_{12} = 0.307 \pm 0.012$$

$$|\Delta m_{21}^2| = (7.50 \pm 0.19) \times 10^{-5} \text{ eV}^2$$

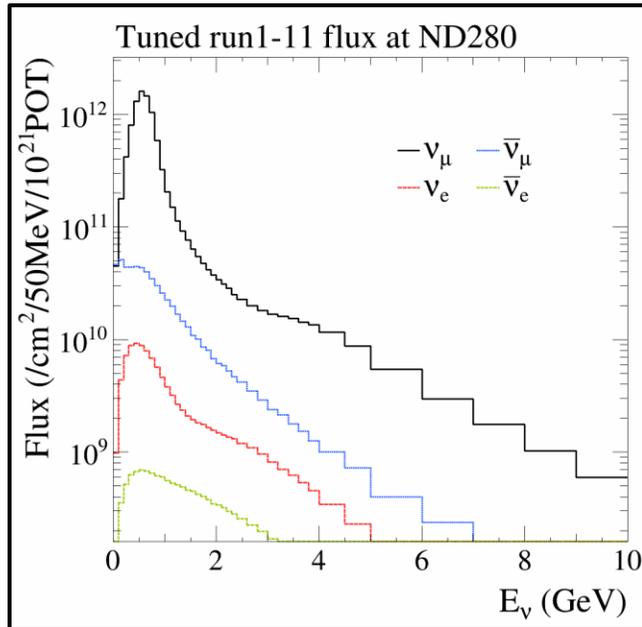
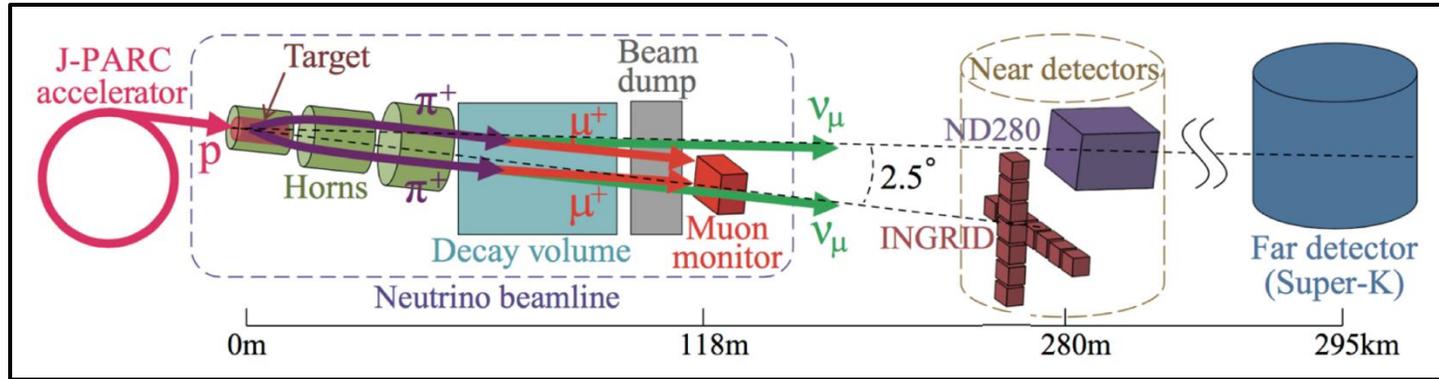
Unanswered questions...

- What is the value of δ_{CP} and is CP symmetry broken?
- Ordering of neutrino mass states?
- Octant of θ_{23} ?
- Is the PMNS matrix complete?

The Tokai to Kamioka (T2K) Experiment

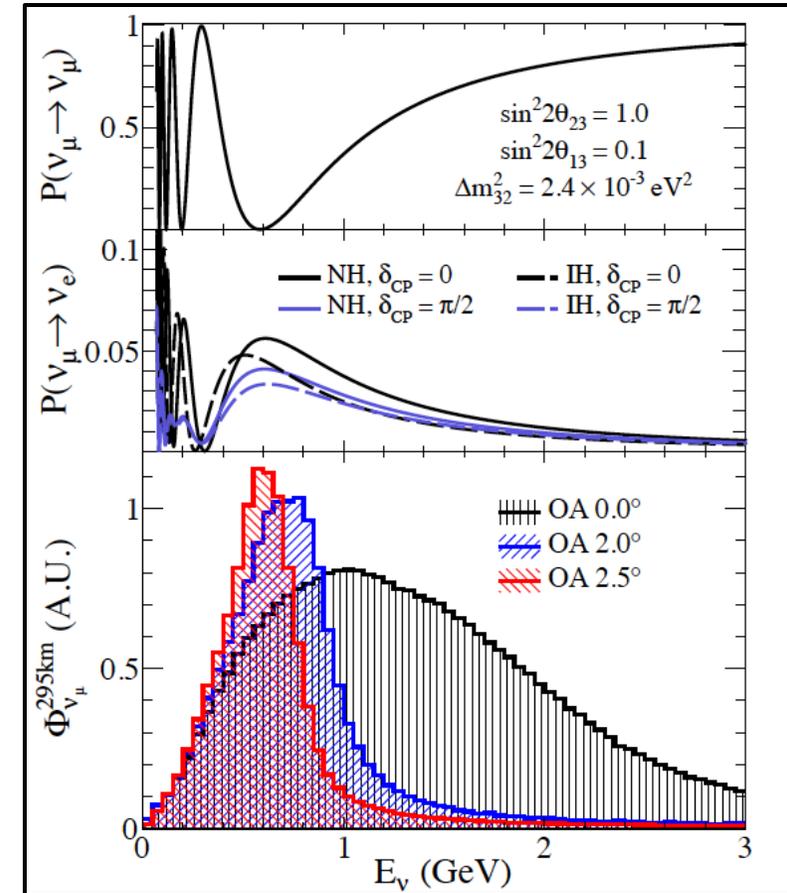


T2K Beam



High-purity ν_μ beam

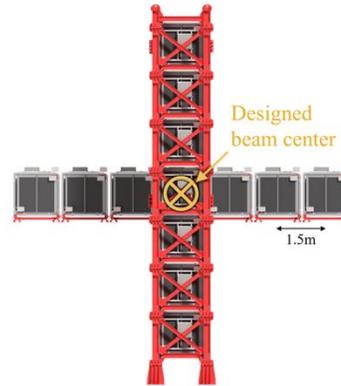
- Use 2.5° off-axis beam to constrain the energy distribution of the neutrino beam.
- Reverse polarity of the horn current to produce a $\bar{\nu}_\mu$ beam.



T2K Near Detectors

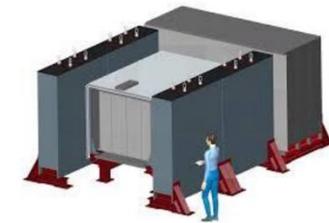
INGRID

- On-axis detector.
- Monitor beam direction/stability.
- Constrain flux systematics and beam direction.



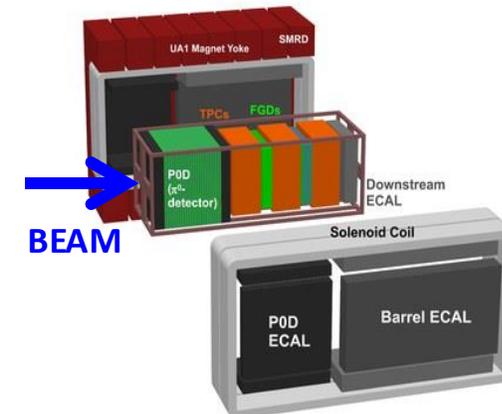
WAGASCI

- 1.5° off-axis.
- Measurement of cross sections on water.



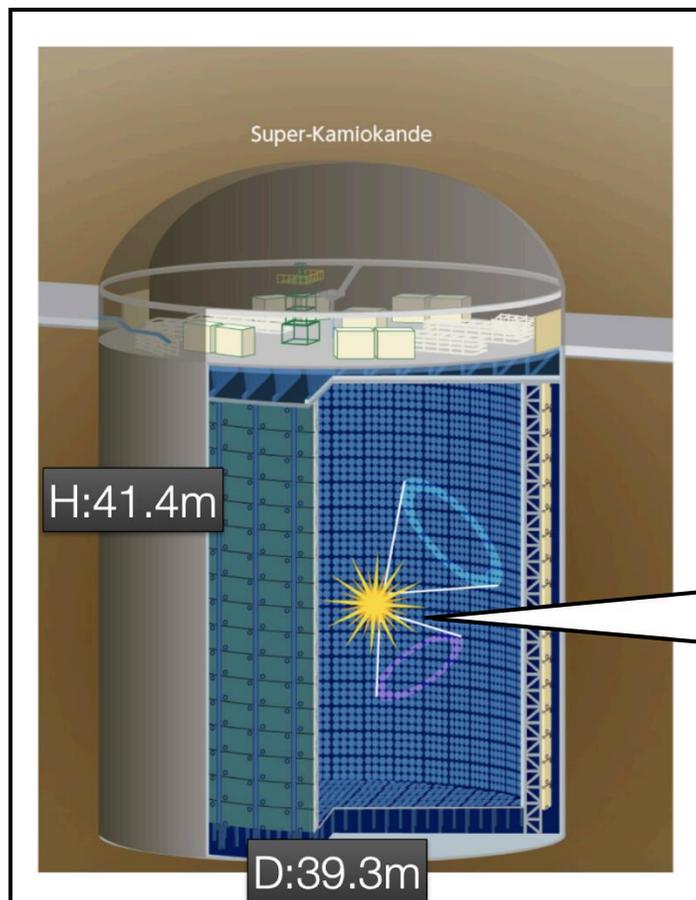
ND280 off-axis detector

- Same direction as Super-K, 2.5° off-axis.
- Measurements of neutrino interaction properties, intrinsic ν_e and wrong-sign backgrounds.
- Constrain flux and cross section systematic uncertainties.
- Upgrade completed in 2024.

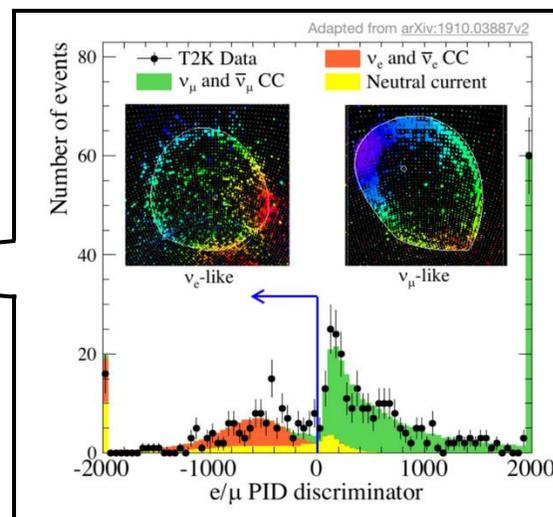


T2K Far Detector (Super-Kamiokande)

The Super-Kamiokande detector: [Nucl. Instrum. Meth. A501 \(2003\) 418-462](#)



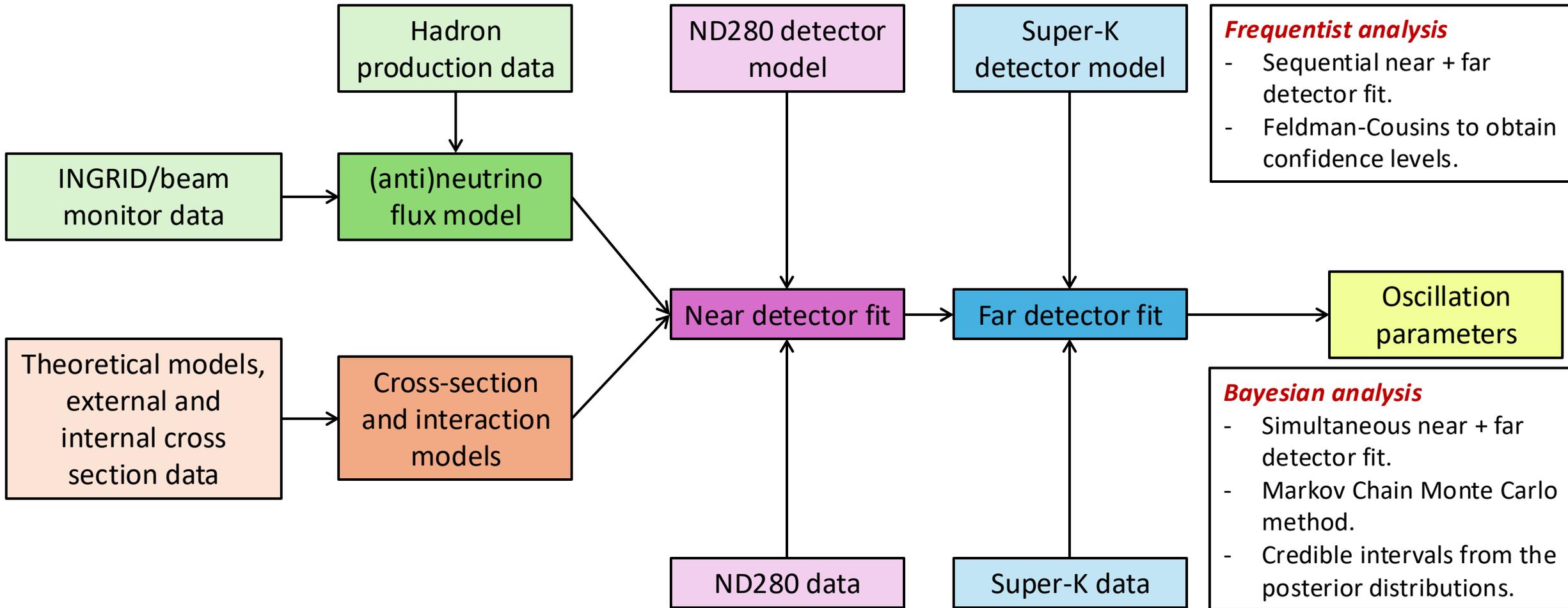
- 50 kton water-Cherenkov detector.
- 2.5° off-axis.
- Approximately 11,000 Photomultiplier tubes (20" diameter).
- Excellent μ/e separation \rightarrow uses "fuzziness" of the ring.



- Doped with 0.01% Gd in 2020.
- Increased loading in 2022.

First loading paper: [Nucl. Inst. Meth. A 1027 166248 \(2022\)](#).
Second loading paper: [Nucl. Inst. Meth. A 1065, 169480 \(2024\)](#).

Oscillation Analysis Strategy



Flux Model Uncertainties

NuFact2025 NA61 talk: <https://indico.cern.ch/event/1528564/contributions/6619924/>

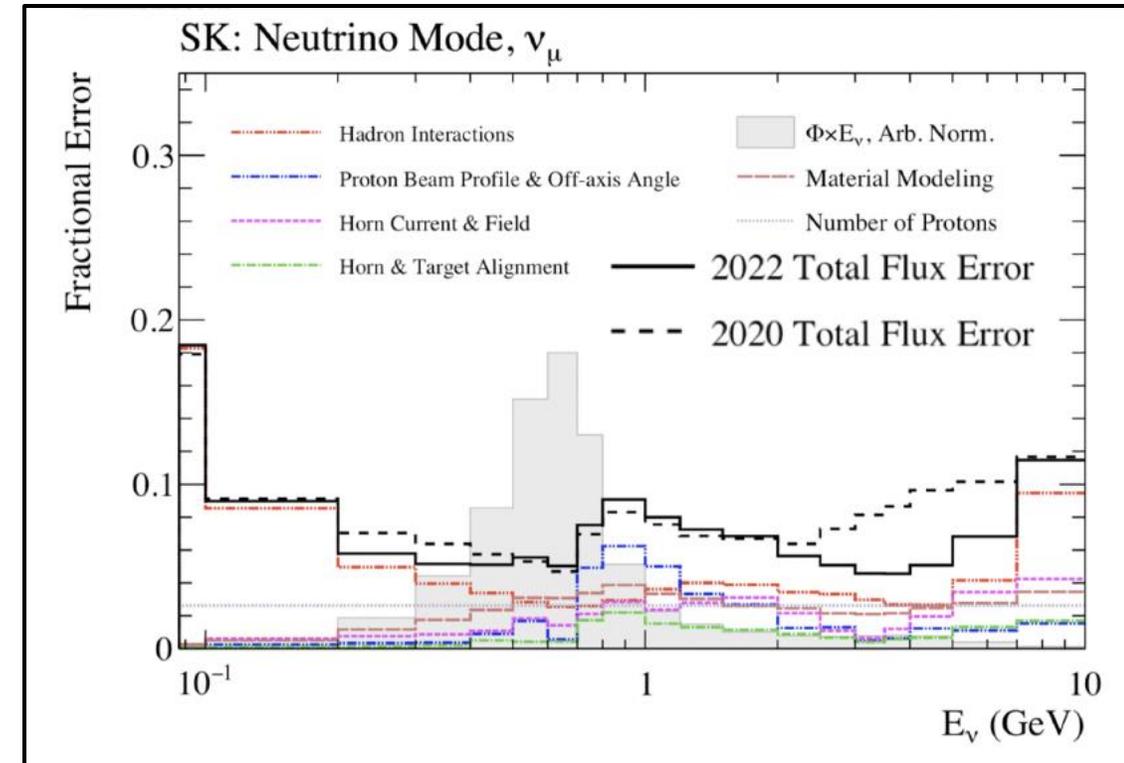
Collide 30 GeV protons with graphite target to produce secondary hadrons.

- Select π^+ using magnetic horns $\rightarrow \nu$ beam.
- Reverse polarity of horn current to select $\pi^- \rightarrow \bar{\nu}$ beam.

Dedicated external measurements of hadron production from NA61/SHINE using replica T2K target.

- Reduce uncertainties at high-energy.

NA61/SHINE publications: [Eur. Phys. J. C 76, 617 \(2016\)](#) and [Eur. Phys. J. C 79, 100 \(2019\)](#)



Interaction Model Uncertainties

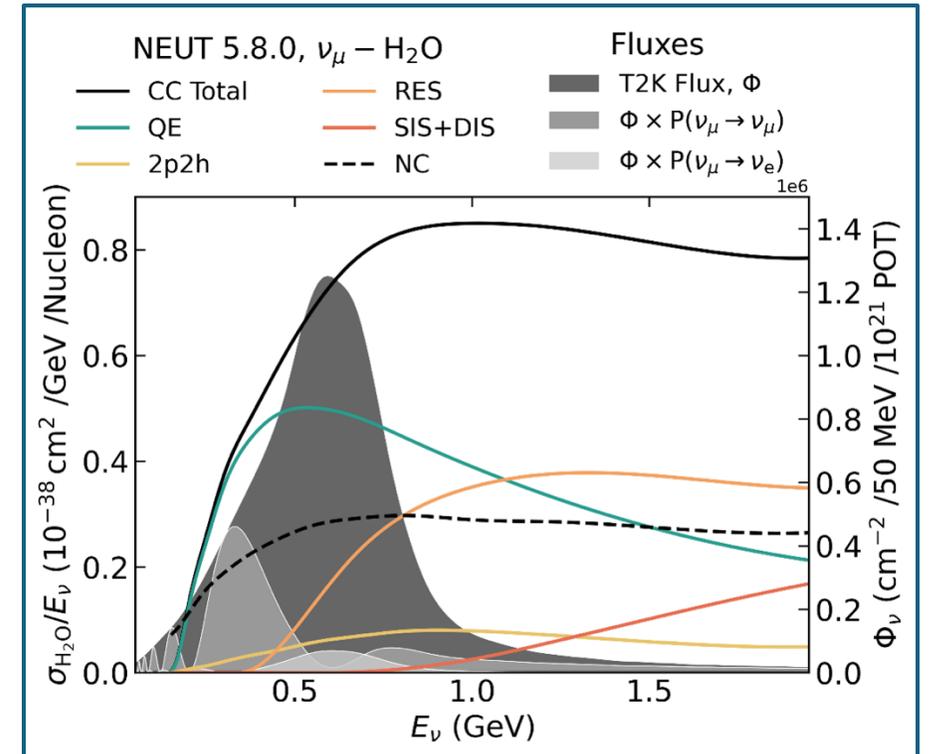
Improved (anti)neutrino interaction models

Charged-Current Quasi-Elastic (CCQE):

- Use theory-driven alternatives to empirical uncertainties.
- Improved uncertainties on nuclear shell structure, nuclear potential and Pauli Blocking.
- Improved description of 2p2h models and nucleon FSI.

CC Resonant (CCRES):

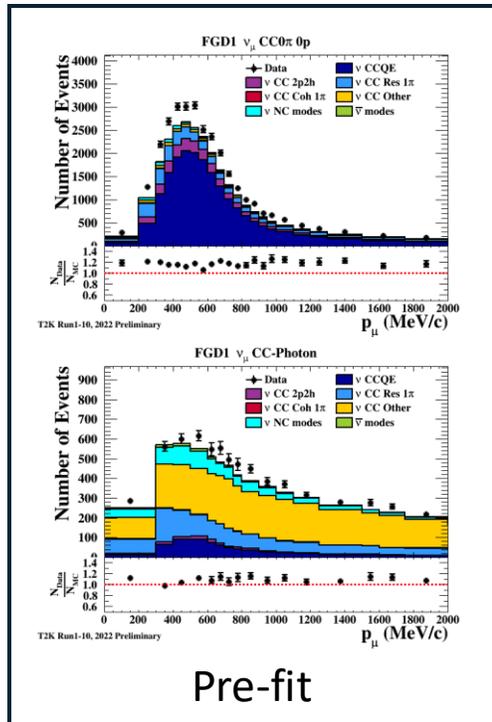
- Based on Rein-Sehgal (RS) model with RFG nuclear model.
- RS parameters benefit from new tune to bubble chamber data.
- New resonance decay uncertainties.
- Effective inclusion of binding energy and its uncertainty.



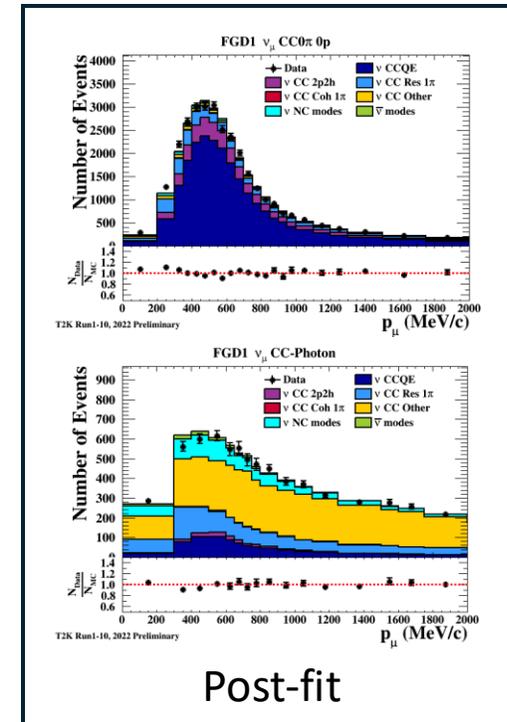
Oscillation Analysis Samples: Near Detector

Near detector: 22 samples classified according to

- Neutrino beam mode.
- Charge of lepton.
- Number of charged pions, protons and photons.
- Interaction on FGD1 (CH) or FGD2 (H₂O+CH).



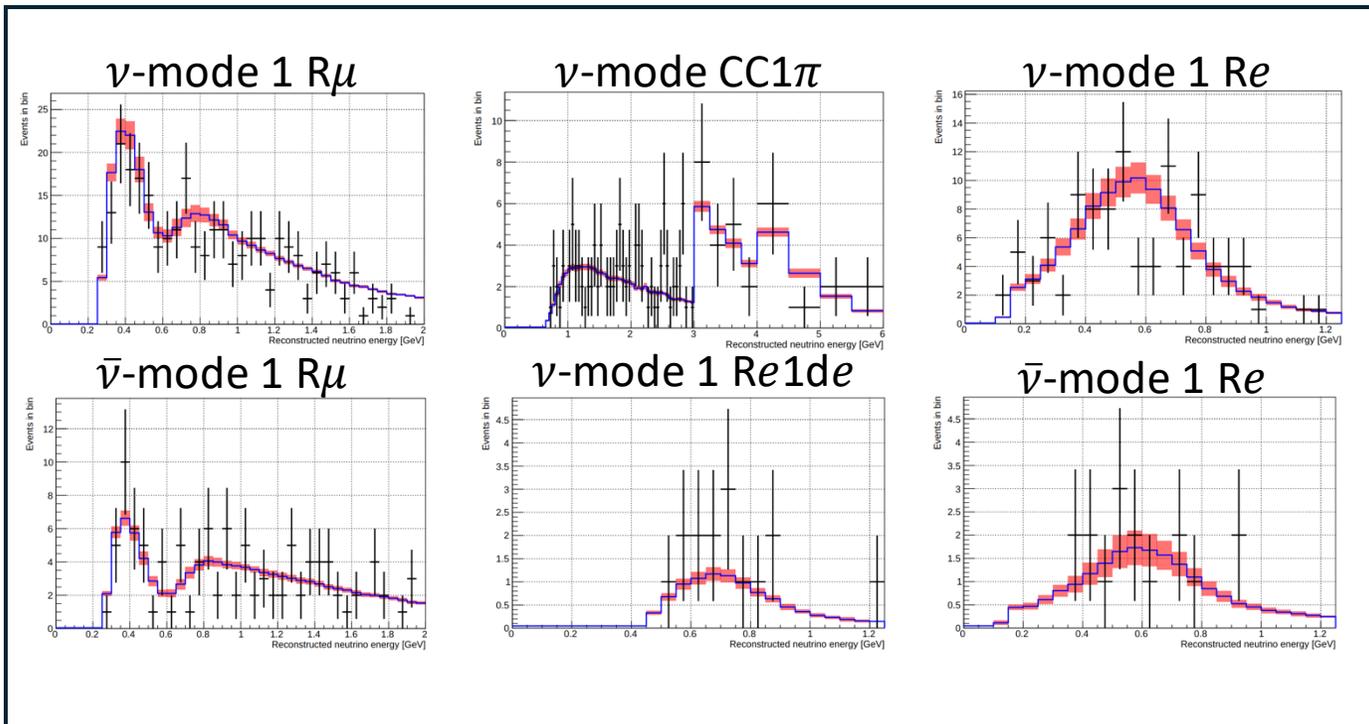
Fit to flux, cross section and detector model parameters to constrain parameters and understand correlations between them.



Oscillation Analysis Samples: Far Detector

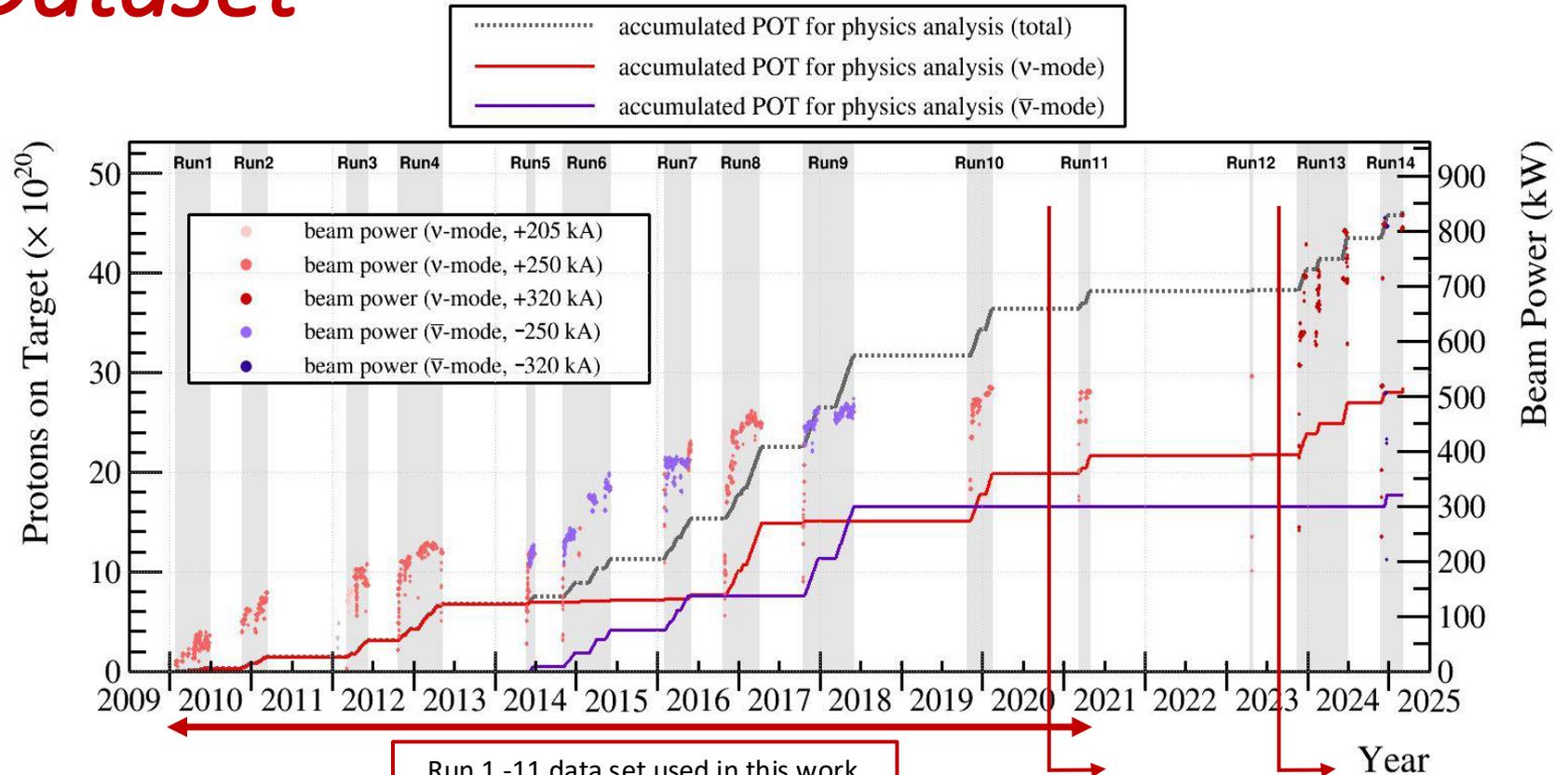
Far detector: 6 samples classified according to

- Neutrino beam mode.
- Number of rings.
- Type of ring -> muon, electron, decay electron.



- Near detector fit results are used to tune the far detector Monte Carlo.
- Event rate uncertainties are reduced:
 - ν_{μ} : $\sim 17\%$ without ND constraint $\rightarrow \sim 3\%$ with ND constraint.
 - ν_e : $\sim 17\%$ without ND constraint $\rightarrow \sim 5\%$ with ND constraint.

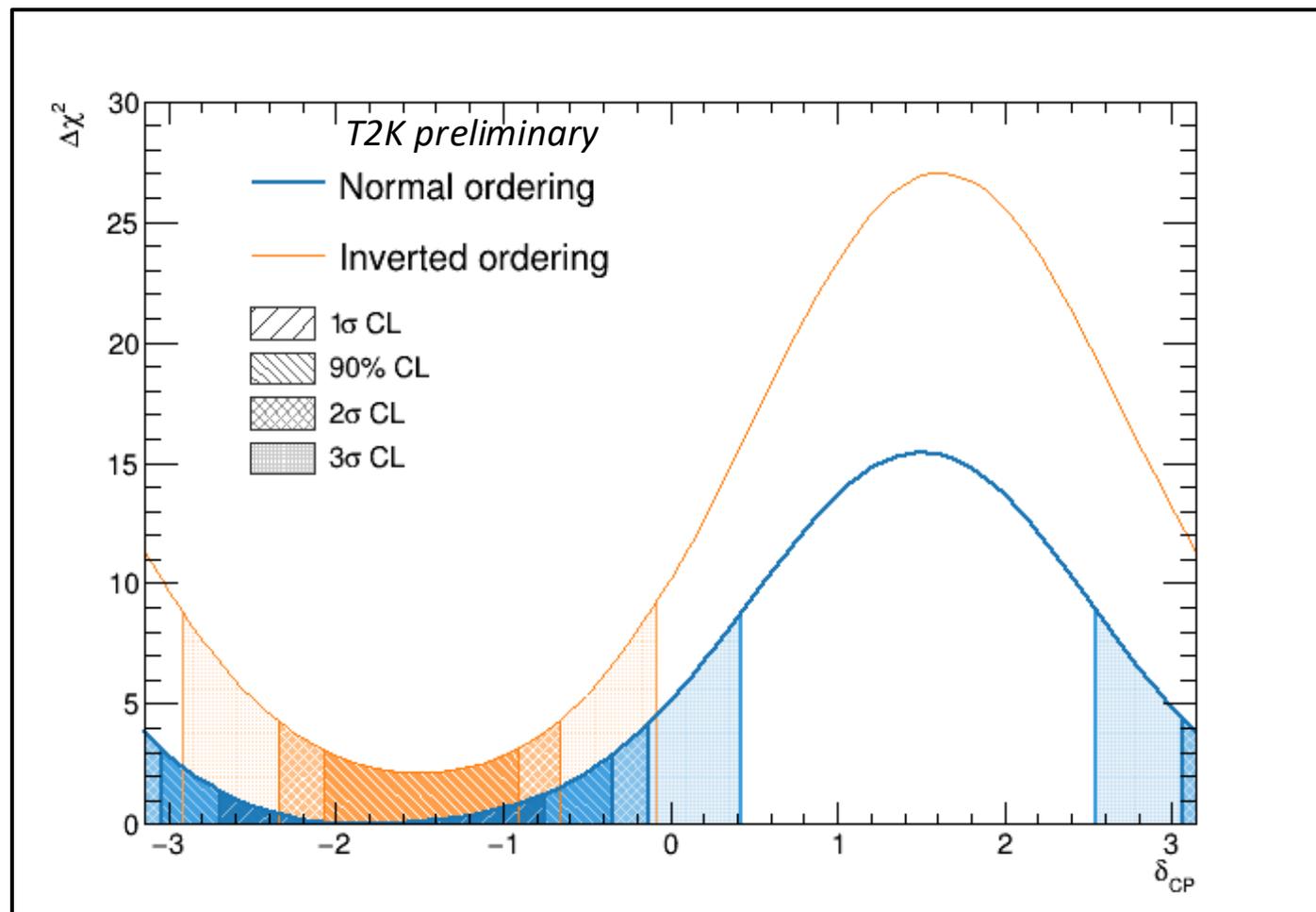
T2K Dataset



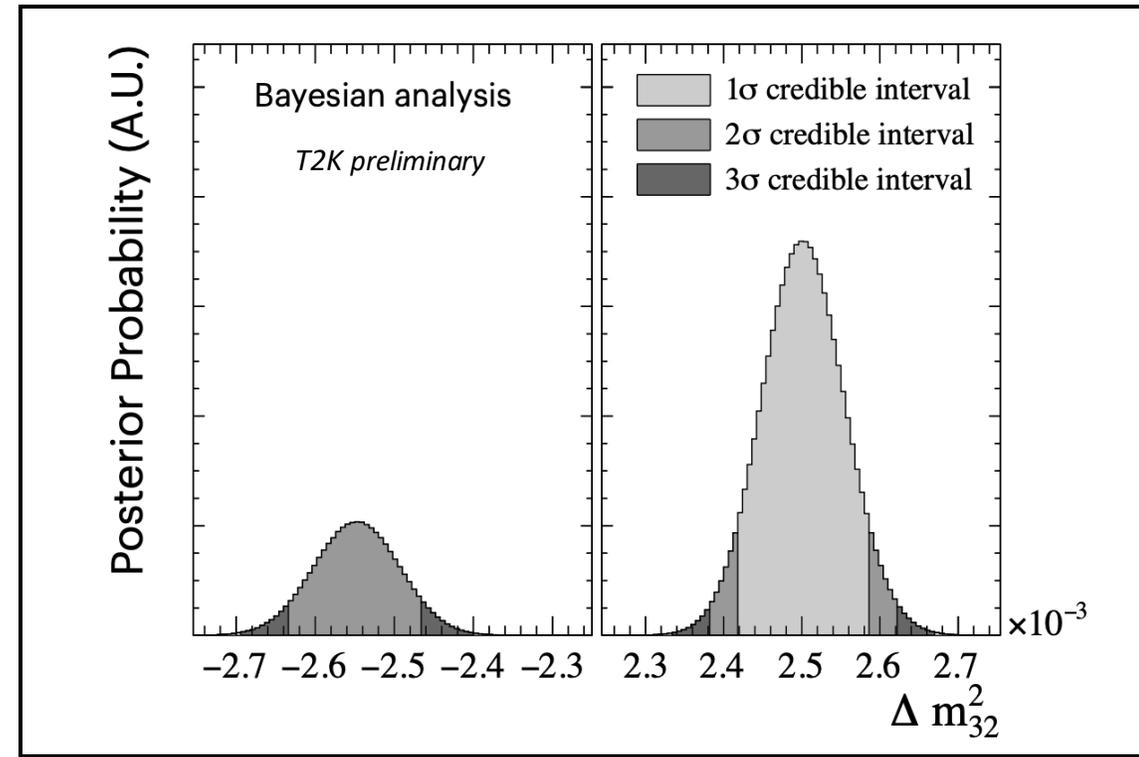
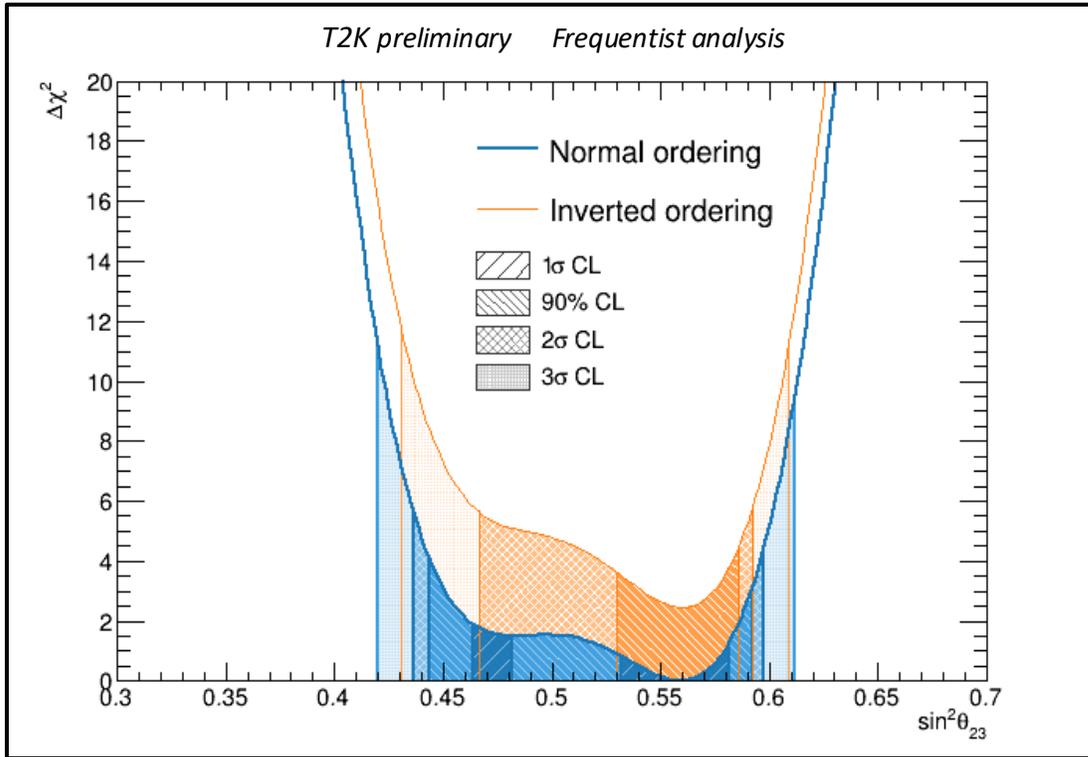
- Increased neutrino-beam dataset → ~10% more statistics.
- New Super-K detector systematic uncertainties.
- Total event rate uncertainties decrease from ~14% → ~6%.

Oscillation Analysis Results: δ_{CP}

- Frequentist results shown above.
- CP Conservation is excluded with 90% confidence level for the nominal analysis.
- In total, 18 alternative models are tested and compared with the nominal analysis.
- Of these, two do not exclude $\delta_{CP} = \pi$ at 90% CL.



Oscillation Analysis Results: θ_{23} , Δm_{32}^2



- Slight preference for normal ordering
 - Bayes factor NO/IO = 3.3
- Slight preference for upper octant of θ_{23}
 - Bayes factor $(\theta_{23} > 0.5)/(\theta_{23} < 0.5) = 2.6$

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m_{32}^2 > 0$)	0.23	0.54	0.77
IO ($\Delta m_{32}^2 < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00

Joint T2K and Super-K Analysis

T2K: shorter baseline, more direct sensitivity to δ_{CP} , but degeneracy around $\delta_{CP} \approx 0, \pi$.

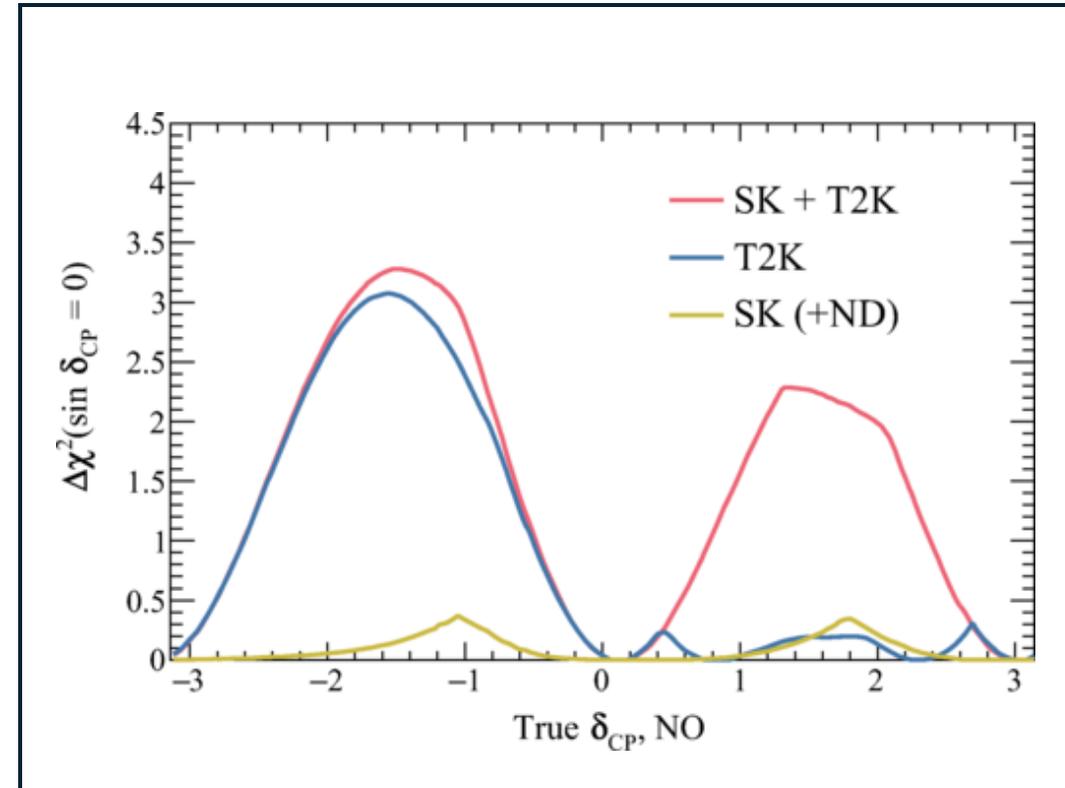
Super-K (atmospheric): Longer baseline, better sensitivity to the mass ordering.

Super-K is part of both experiments

- Joint interaction model for sub-GeV atmospheric and beam neutrinos.
- Common detector model.
- Independent flux models are used.

Motivation: Increased sensitivity to δ_{CP}

Joint analysis of T2K and Super-K atmospheric samples will help break degeneracy between mass ordering and δ_{CP} .



T2K Super-K joint analysis: [Phys. Rev. Lett. 134, 011801](#)

Joint T2K and Super-K Analysis: δ_{CP}

CP-conserving value of the Jarlskog invariant, J_{CP} , is excluded with a significance between 1.9σ and 2.0σ .

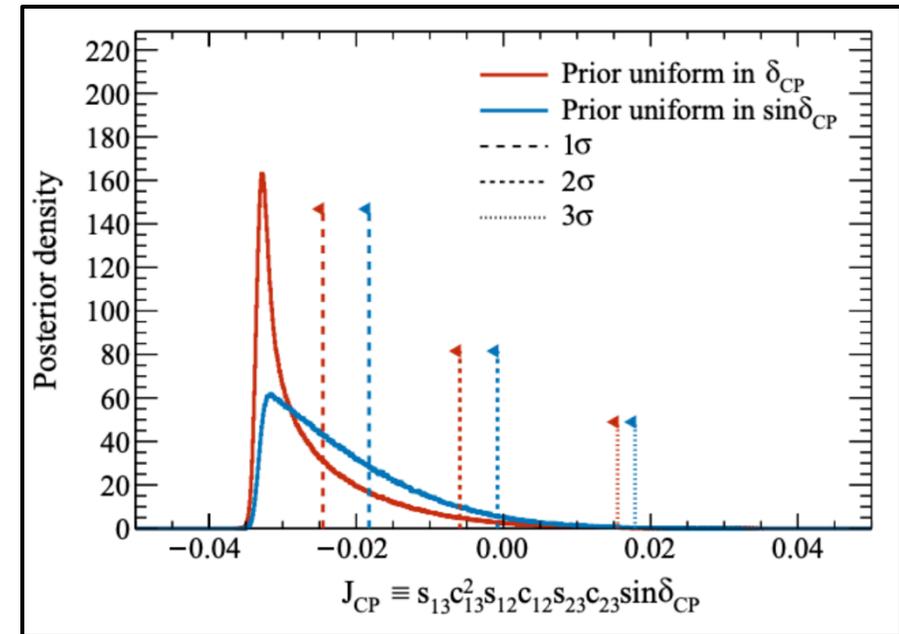
- Significance depends on the analysis considered.

Frequentist analysis:

- CP-conserving value of J_{CP} is excluded at the 1.96σ level.

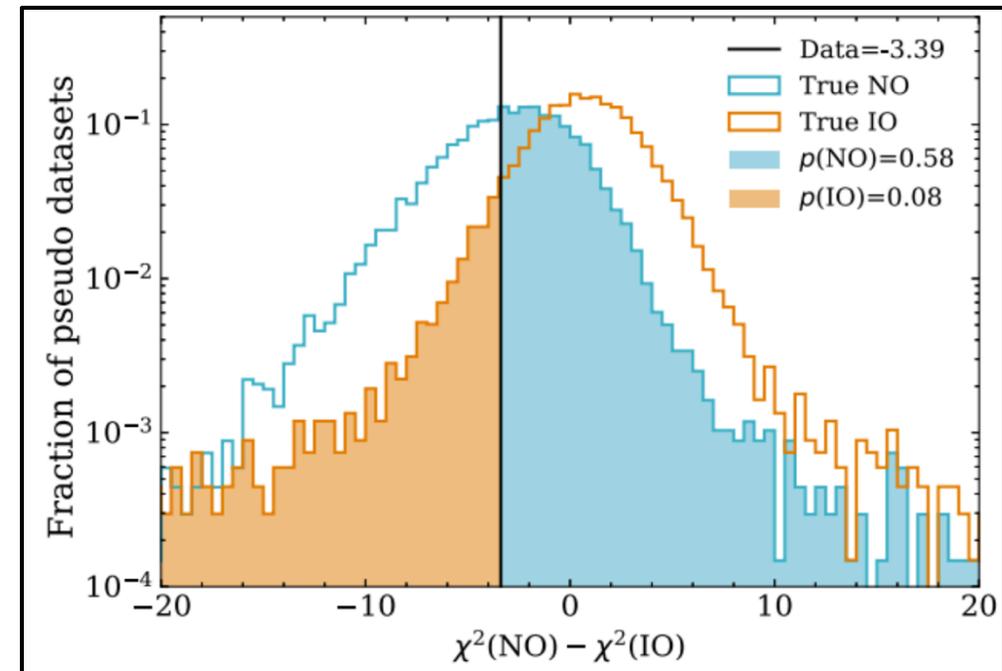
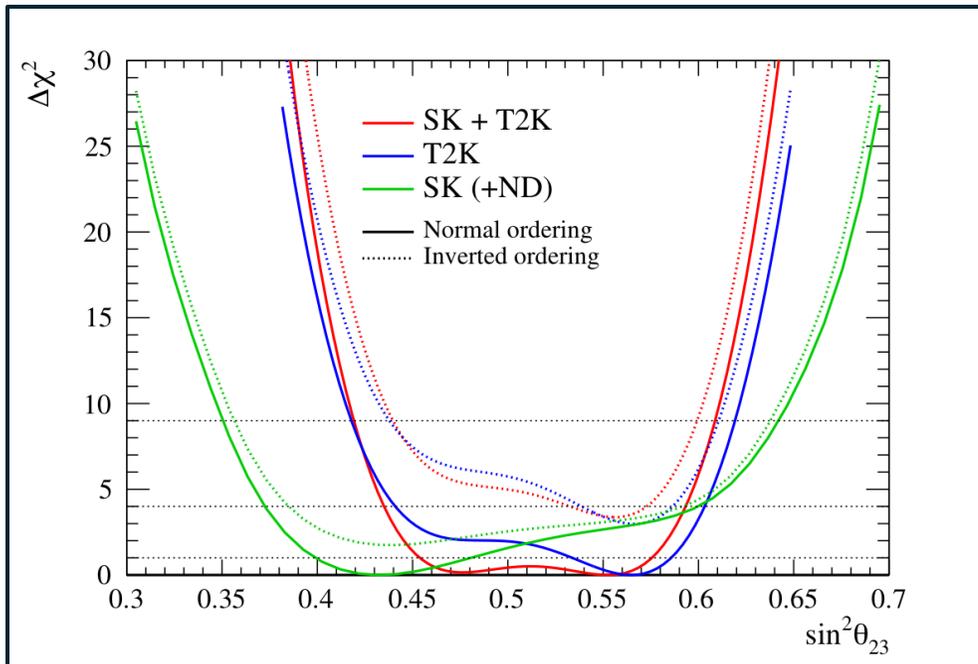
Bayesian analyses:

- Prior uniform in δ_{CP} : CP-conserving value of J_{CP} is outside of the 2.17σ credible interval.
- Prior uniform in $\sin(\delta_{CP})$: CP-conserving value of J_{CP} is outside of the 1.92σ credible interval.



Joint T2K and Super-K Analysis: θ_{23} , Δm_{32}^2

- Super-K and T2K have different preferences for the octant of θ_{23} .
- No strong preference for octant in joint fit.
- Limited preference for normal mass ordering, with the inverted ordering rejected at 1.2σ .
- Results published in [Phys. Rev. Lett. 134, 011801](#)



Joint T2K and NOvA Analysis

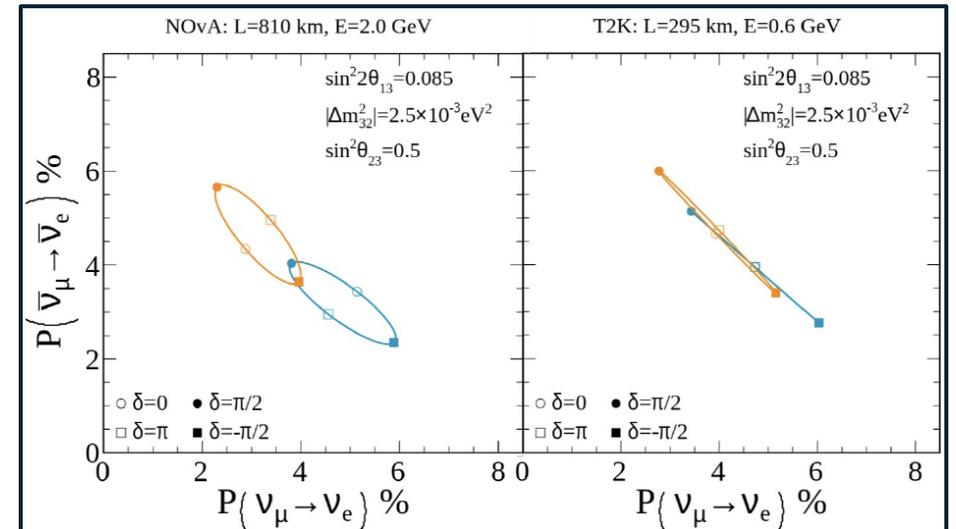
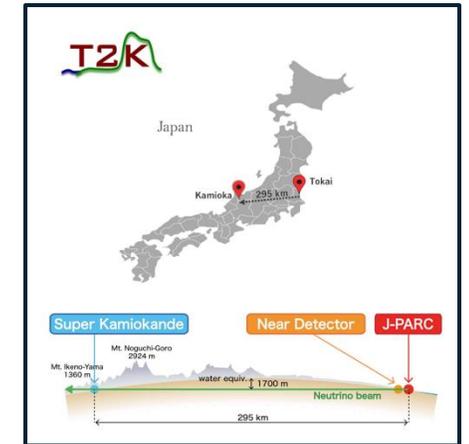
NuFact 2025 NOvA plenary talk, <https://indico.cern.ch/event/1528564/contributions/6642468/>

Different energies and baselines imply differences in sensitivity to oscillation parameters.

Longer baseline of NOvA: better sensitivity to the mass ordering, but degeneracy around $\delta_{CP} \approx \pm \frac{\pi}{2}$.

Shorter baseline of T2K: more direct sensitivity to δ_{CP} , but degeneracy around $\delta_{CP} \approx 0, \pi$.

Joint analysis offers an opportunity to lift the degeneracies.



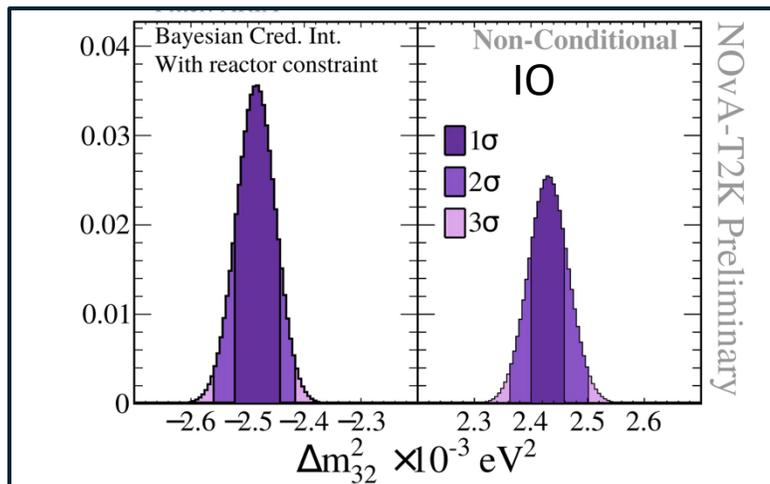
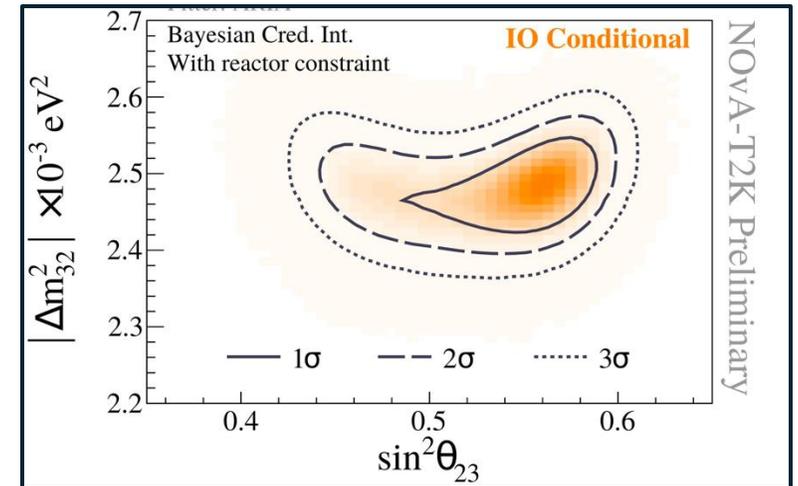
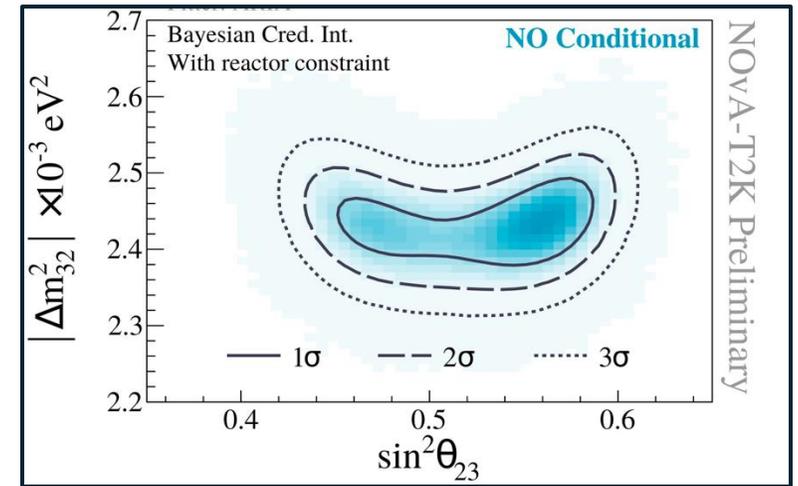
Joint T2K and NOvA Analysis Results: θ_{23} , Δm_{32}^2

Mass ordering and octant of θ_{23}

- Results shown on this slide include a reactor constraint.
- Small preference (not statistically significant) for inverted ordering.
- No preference for the octant of θ_{23} .
- Improved measurement of $|\Delta m_{32}^2|$.

Normal ordering: $|\Delta m_{32}^2| = (2.429^{+0.039}_{-0.035}) \times 10^{-3} \text{eV}^2$

Inverted ordering: $|\Delta m_{32}^2| = (2.477^{+0.035}_{-0.035}) \times 10^{-3} \text{eV}^2$



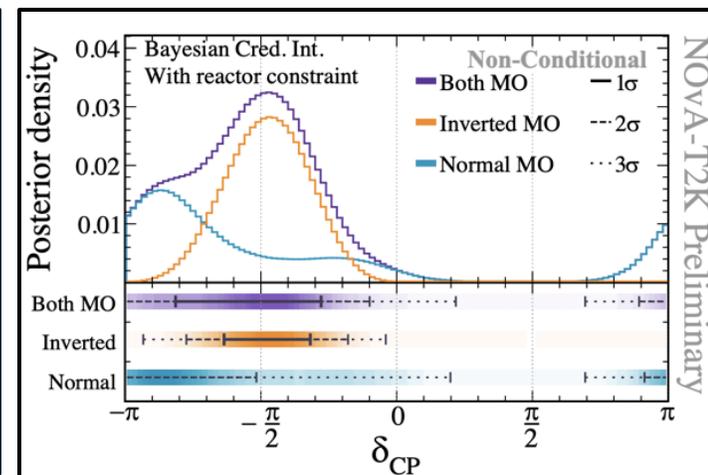
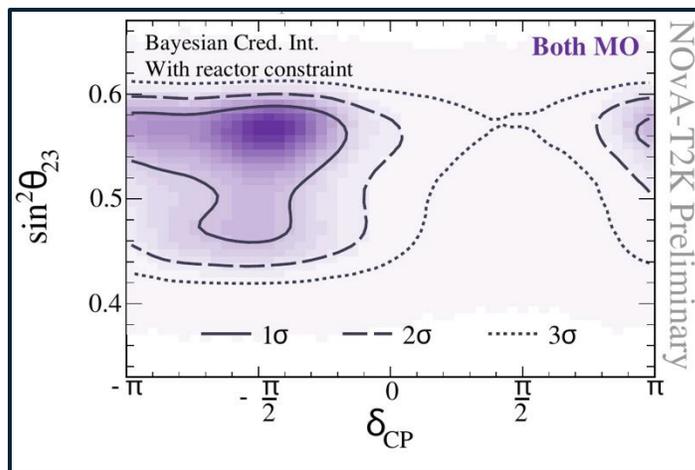
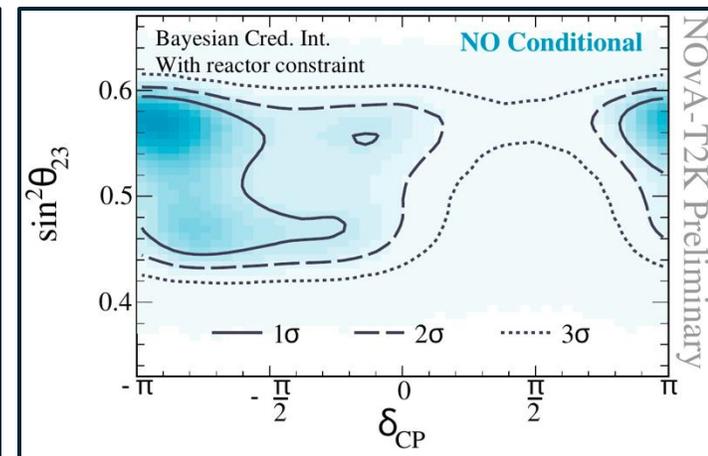
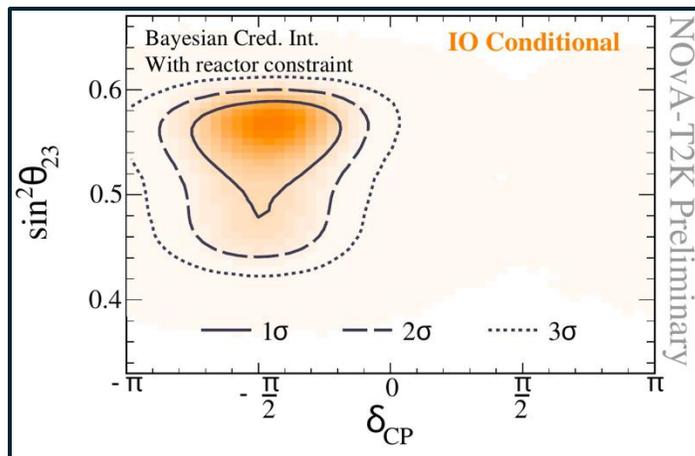
Joint T2K and NOvA Analysis Results: δ_{CP}

Both mass orderings: Higher posterior density around $\delta_{CP} = -\frac{\pi}{2}$.

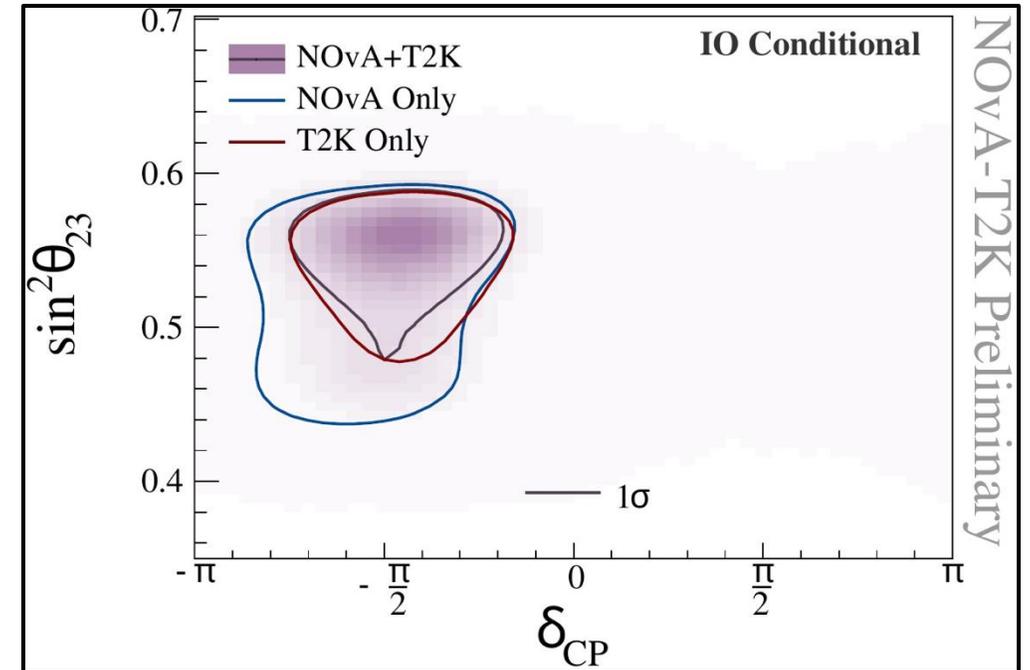
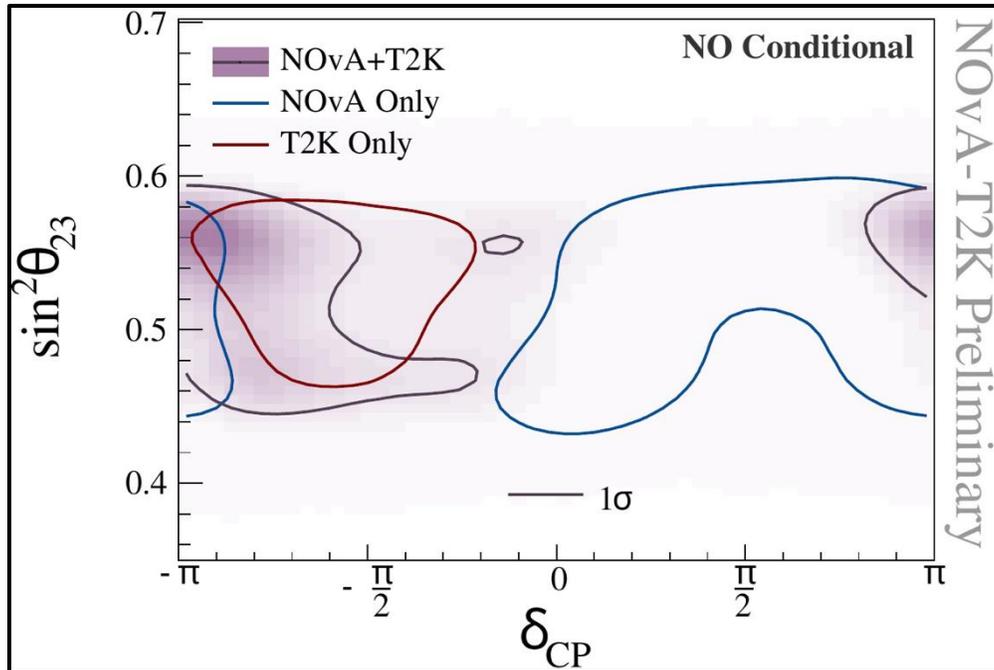
Normal mass ordering: Wider range of values with higher posterior density closer to $\delta_{CP} = \pm\pi$.

Inverted mass ordering: Enhanced preference for $\delta_{CP} = -\frac{\pi}{2}$.

If inverted ordering is the true ordering, there is 3σ exclusion of CP conservation.



Comparing T2K and NOvA Results



- Individual fits from T2K and NOvA are consistent with the joint fit results.
- Constraints for inverted mass ordering are improved.

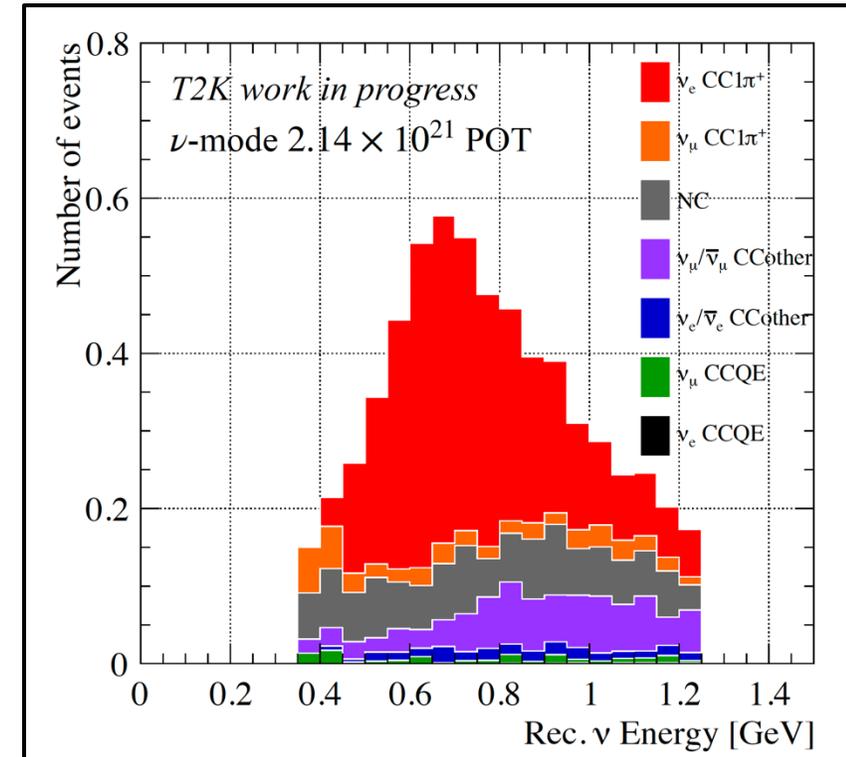
T2K Future: Beamline and Super-K

Beamline upgrades already implemented:

- New Main Ring power supplies allow higher repetition rate
2.48 s \rightarrow 1.36 s.
- Horn current 250 kA \rightarrow 320 kA increases neutrino flux by $\sim 10\%$.
- Beam power increased to 830 kW in June 2024.
- Looking forward to analysing data!

Super-K:

- New $\nu_e \text{CC}1\pi^+$ appearance sample ready for upcoming oscillation analysis.
- New NC $1\pi^0$ sample.
- Improved detector systematics \rightarrow better correlations between single-ring and multi-ring events.
- New data with Gd-loading, runs 12-13.



T2K Future: Near Detectors and Other

ND280:

New samples from pre-upgrade ND280 detector are in development.

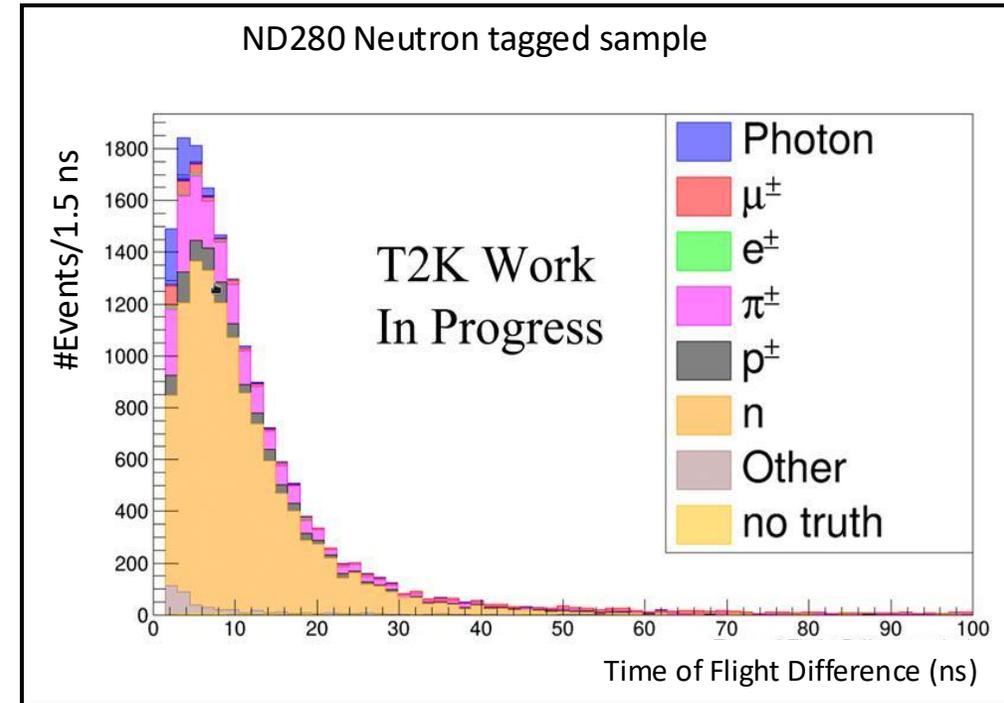
- Anti-neutrino photon selection.
- Neutron tagging in anti-neutrino events.
- 4π solid angle neutrino samples.

WAGASCI:

- Samples from a different off-axis angle.
- Measurements of interactions on water.

Other:

- External constraints for θ_{13} from Particle Data Group include T2K results and thus cannot be used. Developing alternative using reactor only.
- New models are being included in the NEUT interaction generator.



T2K Near Detector Upgrade

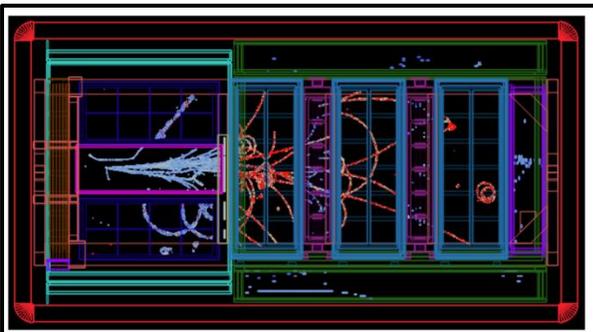
POD detector replaced with

- Super Fine-Grained Detector (SFGD).
- 2 High Angle Time Projection Chambers (HATPCs).
- Time of Flight (ToF) detector.

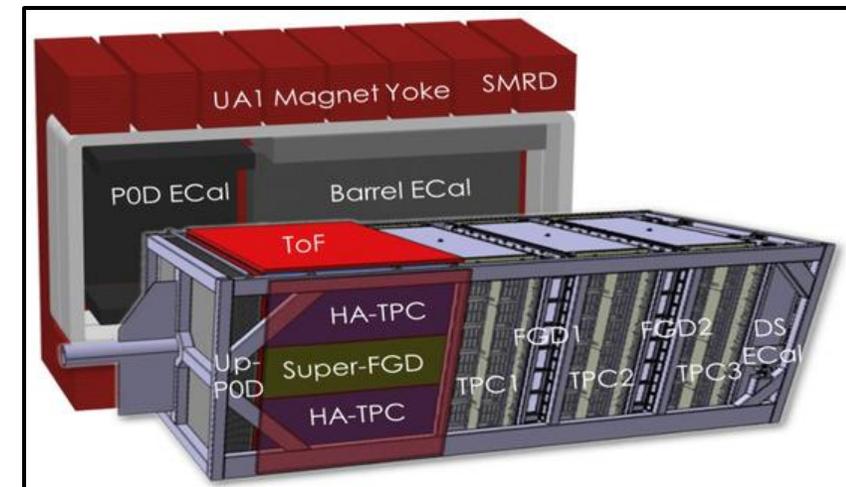
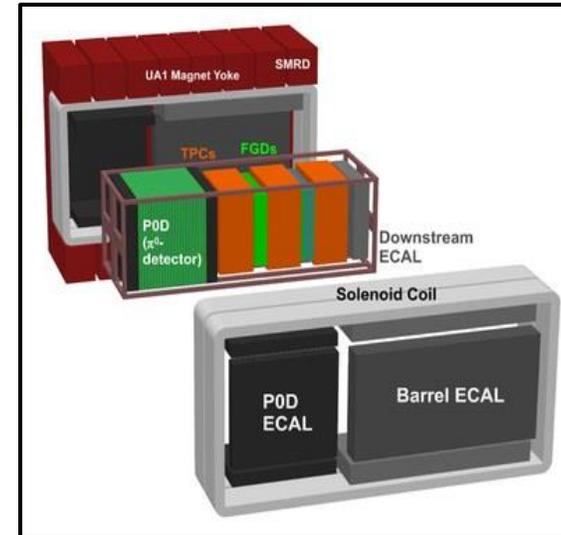
Aim to reduce systematic uncertainties

- Improved acceptance and efficiency.
- Lower detection thresholds.
- Kinematic reconstruction of neutrons.

First data taken in 2024!



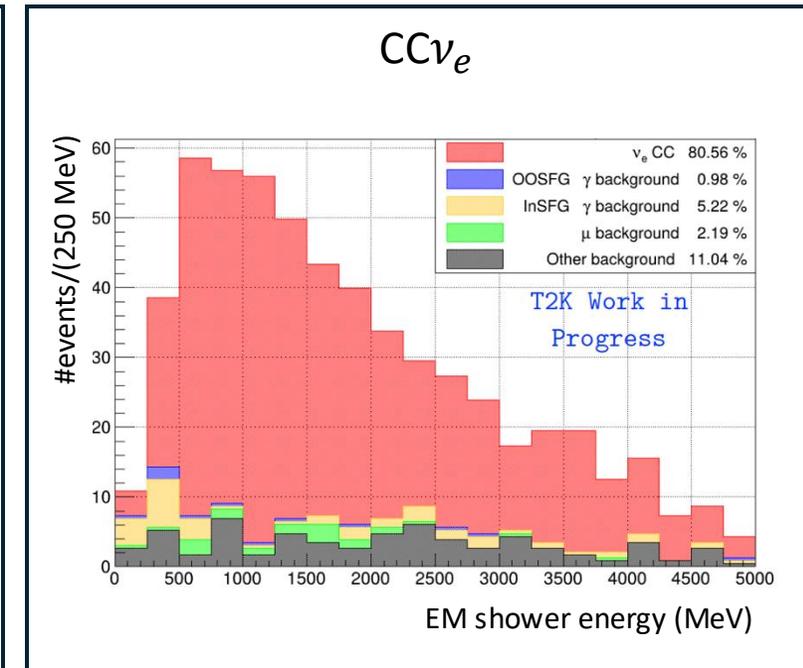
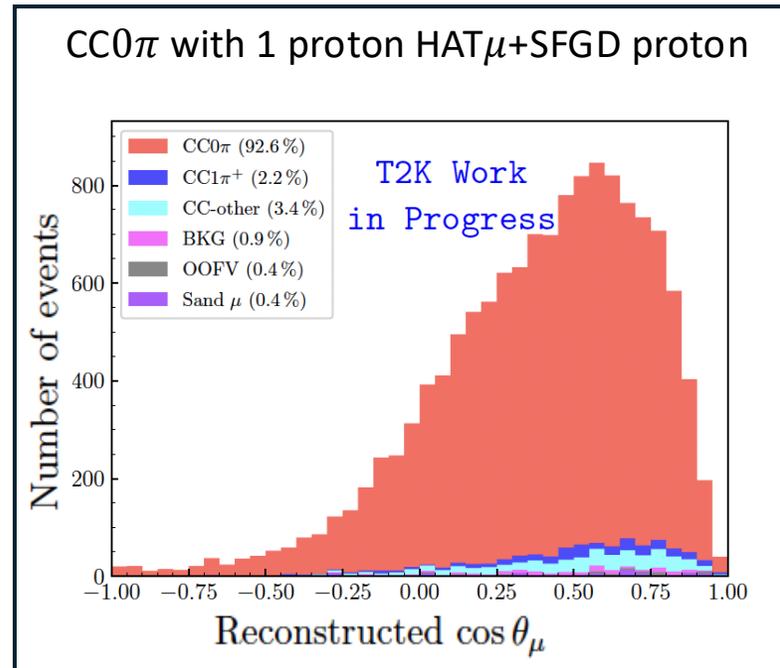
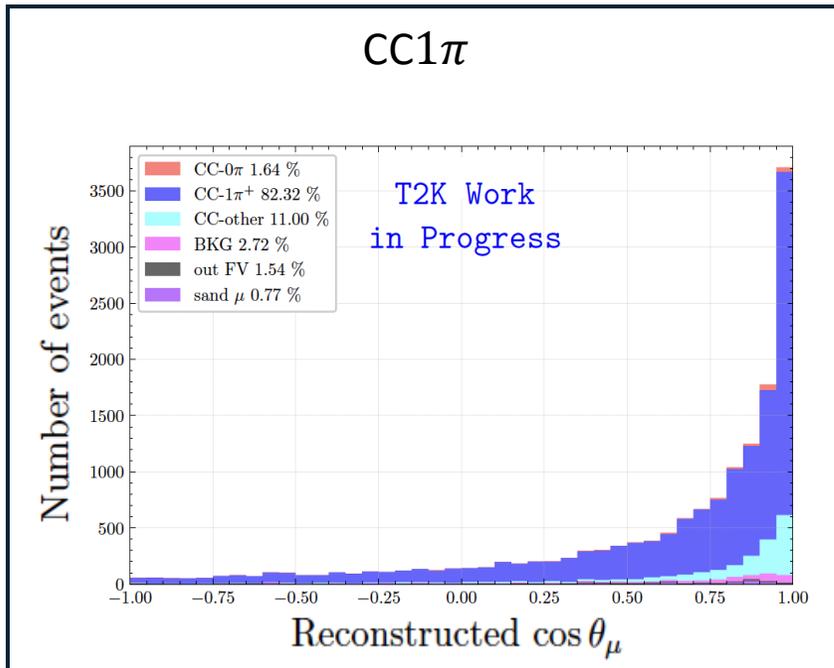
Run 16847,
7th June 2024



T2K Near Detector Upgrade Samples

Upgraded ND280 provides an exciting opportunity to improve near detector input to oscillation analysis.

- Improved constraints of flux and cross-section systematic uncertainties.
- Higher efficiency selections.
- Better (4π) acceptance.
- Neutron kinetic energy measurements using time of flight
- Lower threshold for proton tracking



Summary

New T2K oscillation analysis with 10% additional statistics

- CP symmetry excluded at 90% CL.
- Weak preference for normal mass ordering and upper octant of θ_{23} .

Joint T2K and Super-K analysis

- CP-conserving value of the Jarlskog invariant, J_{CP} , is excluded with a significance between 1.9σ and 2.0σ .
- Limited preference for normal mass ordering.

Joint T2K and NOvA analysis

- No clear preference for mass ordering.
- Improved precision for $|\Delta m_{32}^2|$.
- CP conserving values outside of 3σ for inverted mass ordering.

Exciting future for T2K!

- New results and samples from ND280 upgrade!
- Analysis of data obtained after beamline upgrades!
- New samples from Super-K!

