Joint Analysis between Super-Kamiokande atmospheric and T2K data

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Zhenxiong Xie

King’s College London

Zhenxiong.xie@kcl.ac.uk

Neutrino Oscillation

Neutrino flavor (interaction) eigenstates are the superimposition of the mass eigenstates.

Mixing (PMNS matrix) of the Hamiltonian eigenvectors:

Atmospheric **Reactor** **Solar**

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

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

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

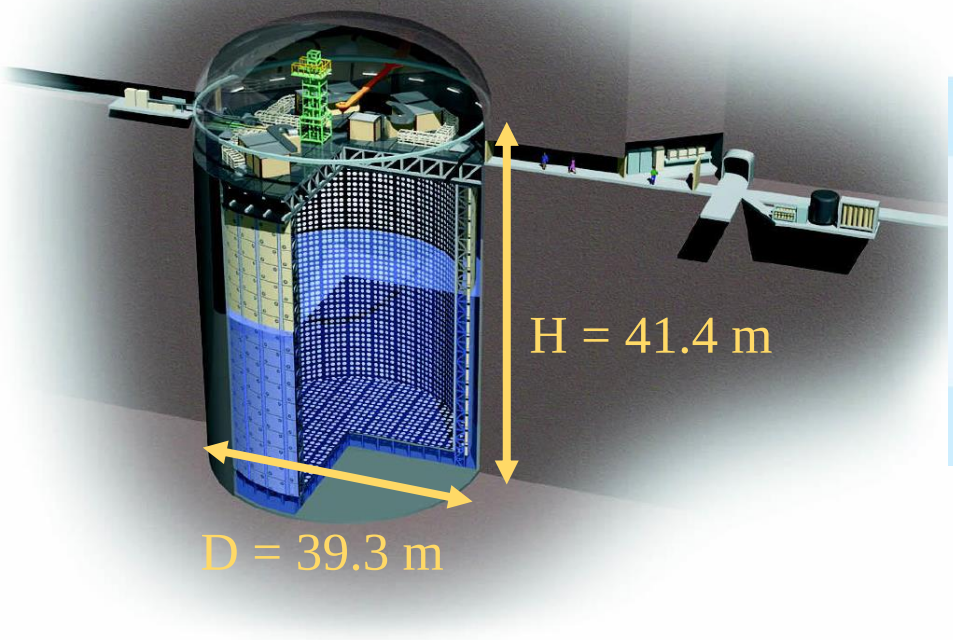
The flavor changes when the neutrino propagates long distance → **Neutrino Oscillation**

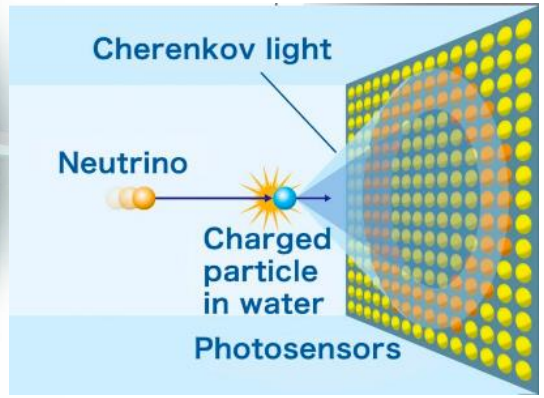
Open questions:

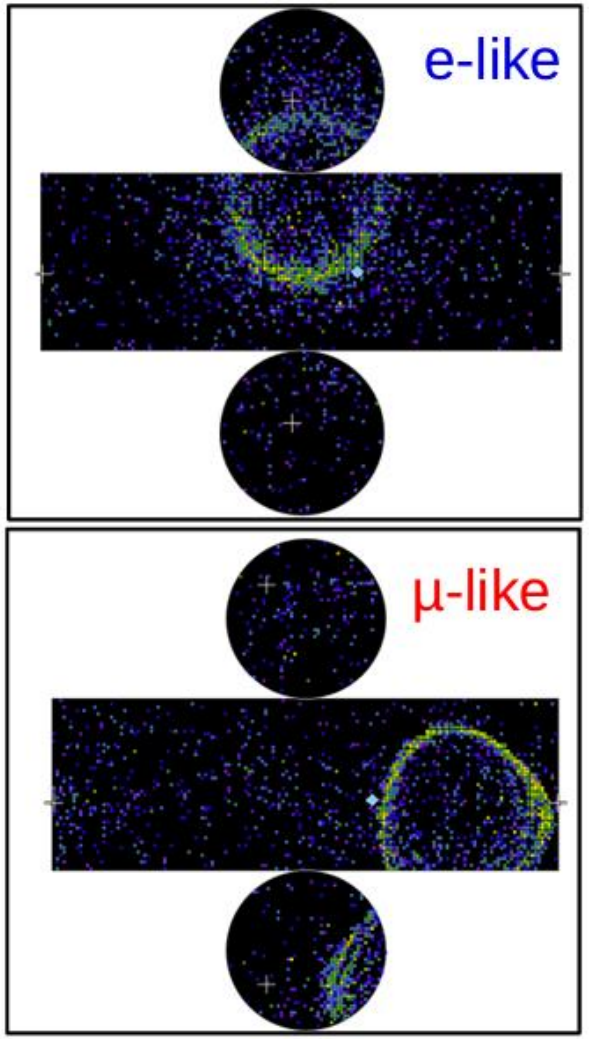
- CP symmetry → value of δ_{CP}
- Mass ordering → sign of Δm^2_{32}
- Octant of θ_{23} → $\theta_{23} > \frac{\pi}{4}$ or $\theta_{23} < \frac{\pi}{4}$

Super-Kamiokande (Super-K)

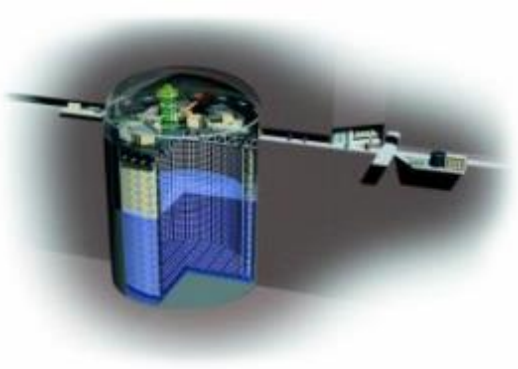
- Water Cherenkov neutrino experiment
- 50 kton of pure water, 22.5 kton of fiducial mass
- 11,129 inner detector (ID) PMTs (20 inch)
- 1885 outer detector (OD) PMTs (8 inch)
- Direction/particle ID are reconstructed from the Cherenkov rings

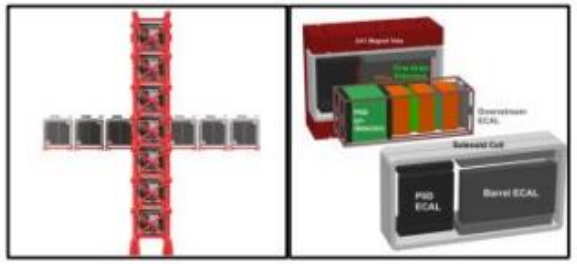


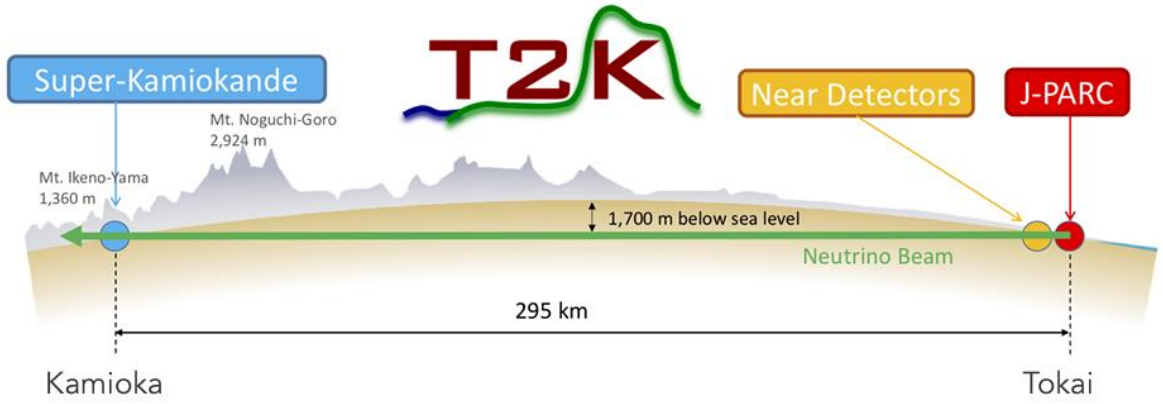




T2K experiment





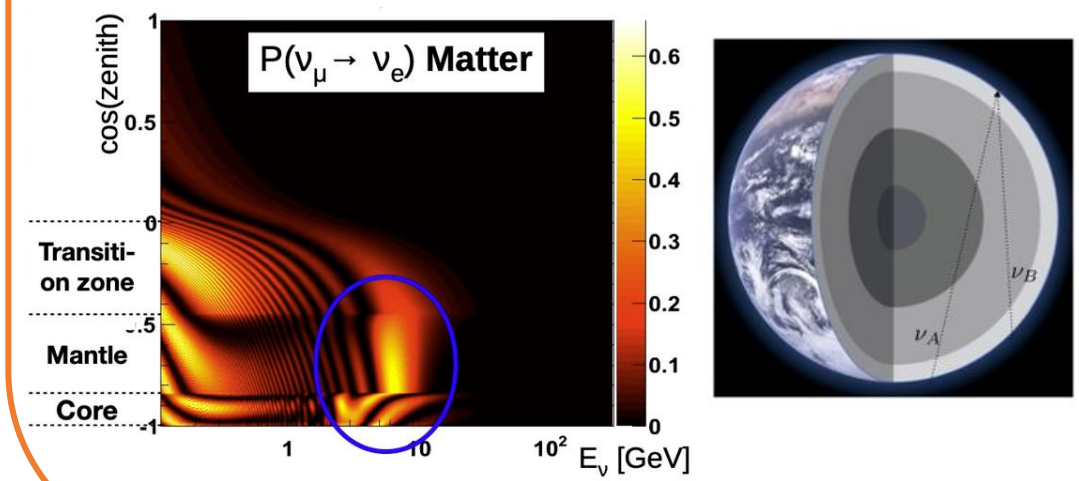


- 295 km baseline, 2.5° off-axis
- $\nu_\mu/\bar{\nu}_\mu$ beam with a flux peaked at 0.6 GeV, it's run either in neutrino or anti-neutrino mode
- ND280 constrains the flux and cross section systematic uncertainties
- Use Super-K as the far detector

Motivation of the joint fit between Super-K atmospheric and T2K data

Atmospheric neutrinos in Super-K

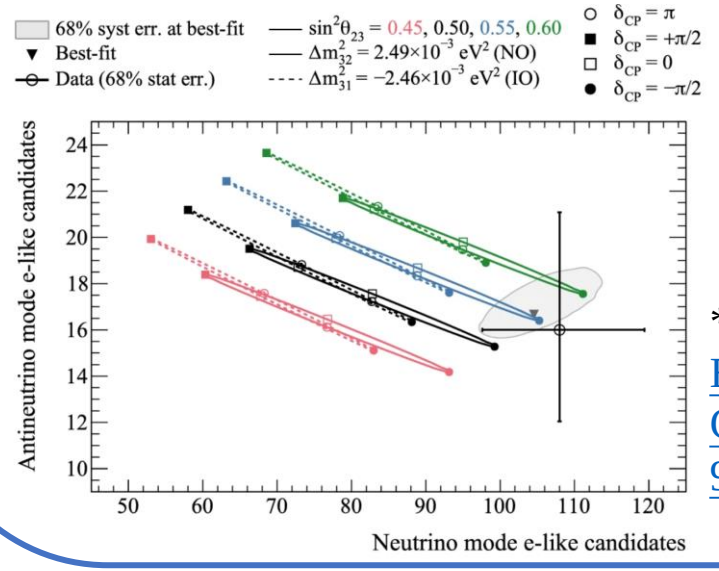
- Resonance in earth mantle and core in Multi-GeV region, only for neutrinos in normal and anti-neutrinos in inverted mass ordering (MO)
- SK Atmospheric neutrinos are sensitive to MO



*Plots from C. Bronner @ PANE 2018

Accelerator neutrinos in T2K

- T2K has better sensitivity to δ_{CP} from ν_e appearance channel, and to $\Delta m^2_{32}, \theta_{23}$ from ν_μ disappearance channel
- In T2K, δ_{CP} and MO have similar effect on the $\nu_e/\bar{\nu}_e$ event rates (degeneracy of oscillation parameters)



*Plots from Eur.Phys.J. C 83 (2023) 9, 782

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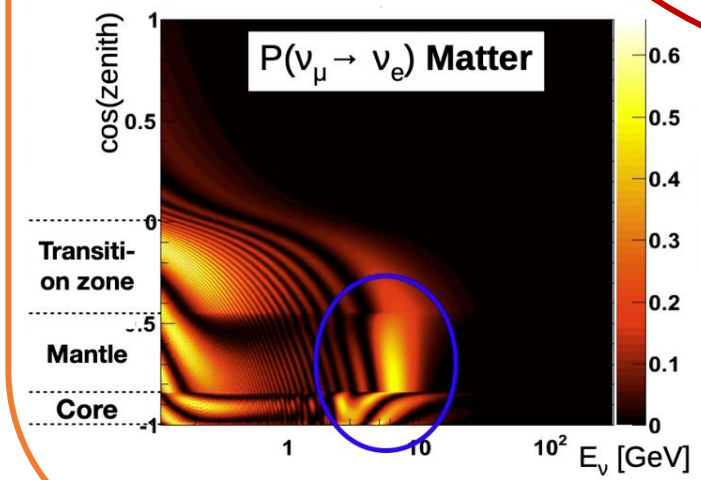

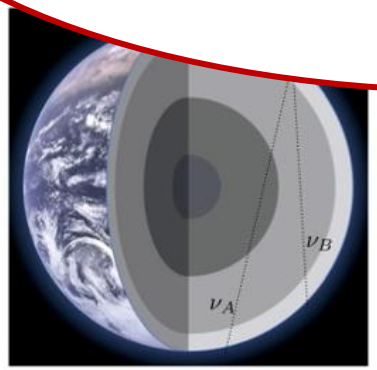

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JOINT FIT

- Break the degeneracy
- Better constraints on MO, δ_{CP}, and mixing parameters

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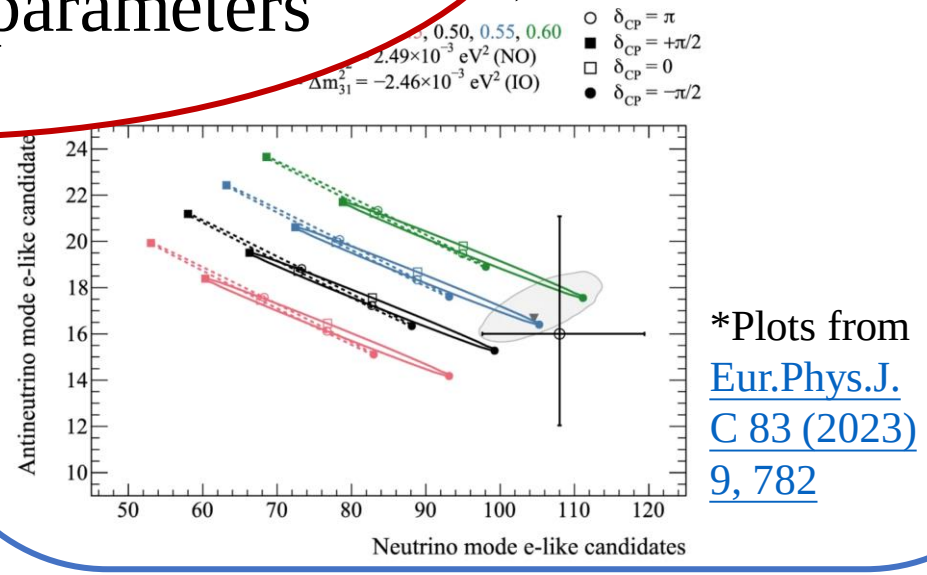

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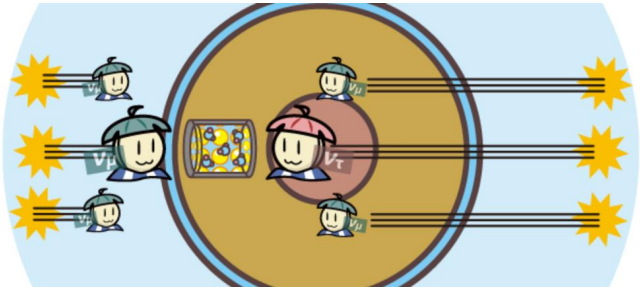
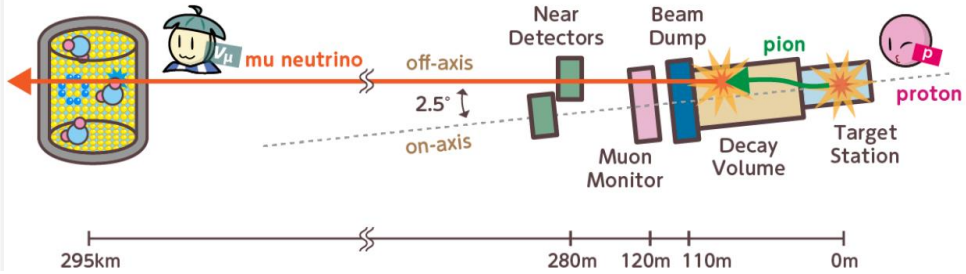
SK-T2K joint analysis





Systematic model

Flux:

- The beam and atmospheric flux models are independent

Cross-section:

- Low energy samples (T2K & SK Sub-GeV) with ND constraint
- High energy samples (SK high energy): modified SK model including additional systematics uncertainties

Detector:

- There is correlation between SK and T2K detector errors

*Details of the systematic model can be found in A. Eguchi @ NNN2023

Data

Super-K atmospheric

- Super-K phase IV (PTEP 2019 (2019) 5, 053F01)
- 3244.4 days of data taking

T2K

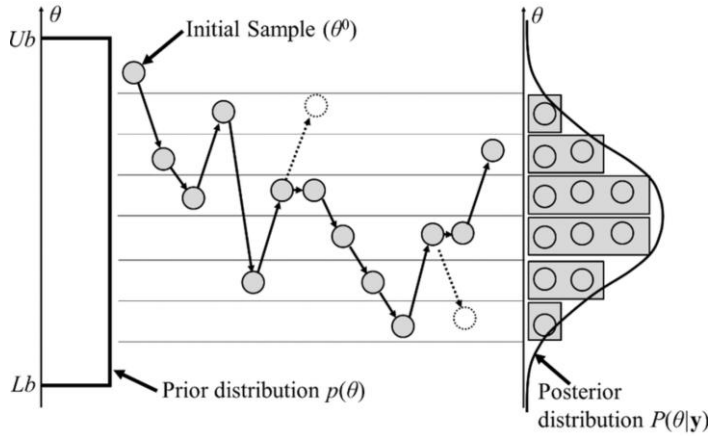
- T2K run 1-10 (Eur.Phys.J.C 83 (2023) 9, 782)
- Neutrino mode: 19.7×10^{20} POT
- Antineutrino mode: 16.3×10^{20} POT

Analysis method

- There are 4 analyses developed based on a common model for this joint fit: two Bayesian analyses and two frequentist analyses;
- There are differences in technical implementation, binning, and statistical methodology among the analyses methods.

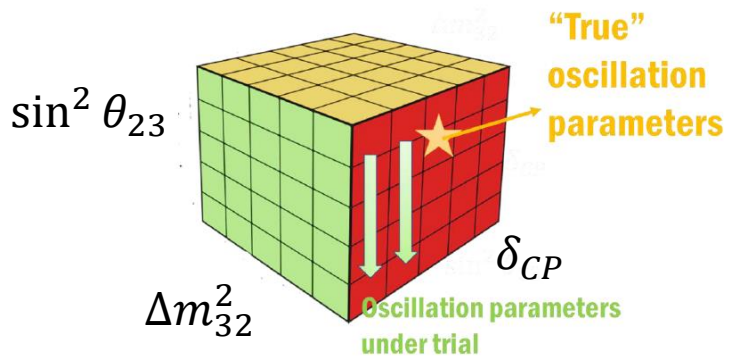
Bayesian Analyses

- Markov Chain Monte Carlo (MCMC) to evaluate marginal likelihoods for the oscillation parameter of interest



Frequentist Analyses

- Profile likelihood on the grids of oscillation parameters of interest



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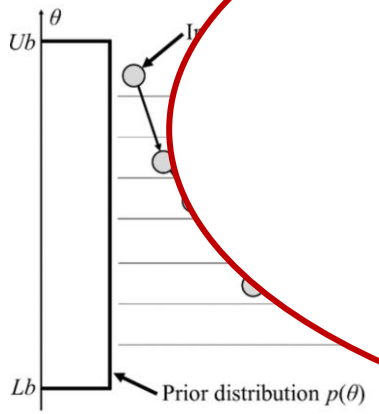

Frequentist Analyses

lihood on the grids of
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"True"
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CP
parameters
trial

- This presentation will show the results from Bayesian analyses, between which great consistency is found.
- Gaussian constraint of $\sin^2 2\theta_{13} = 0.853 \pm 0.0027$ from reactor experiments is applied in the followed results
- Frequentist analyses are under progress.

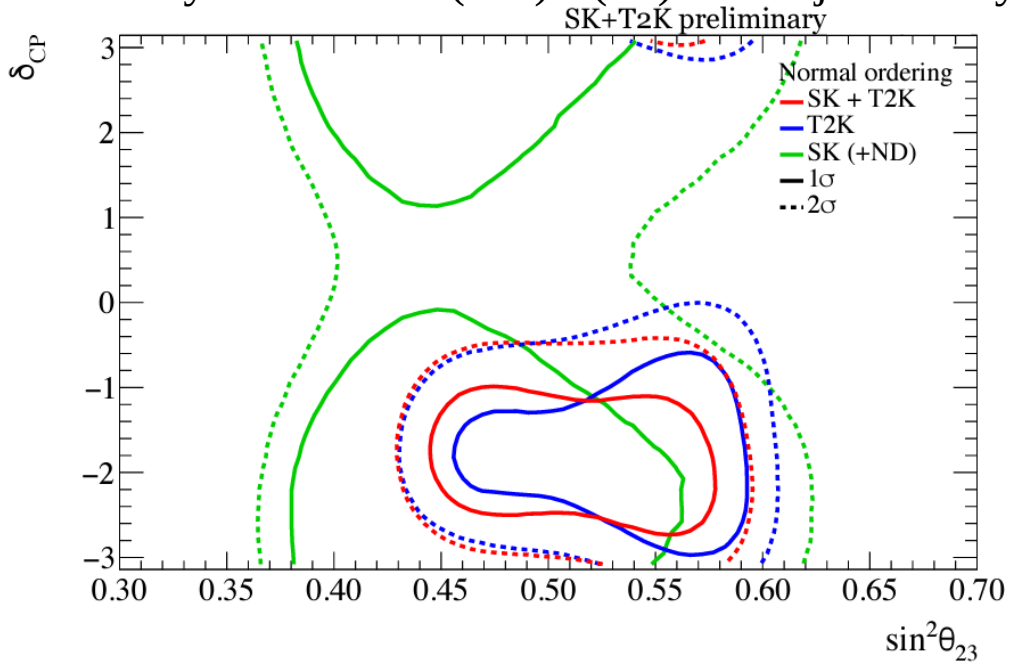
*The plots are from one of the Bayesian analyses, which has compatible results with another.
A. Eguchi@NNN2023

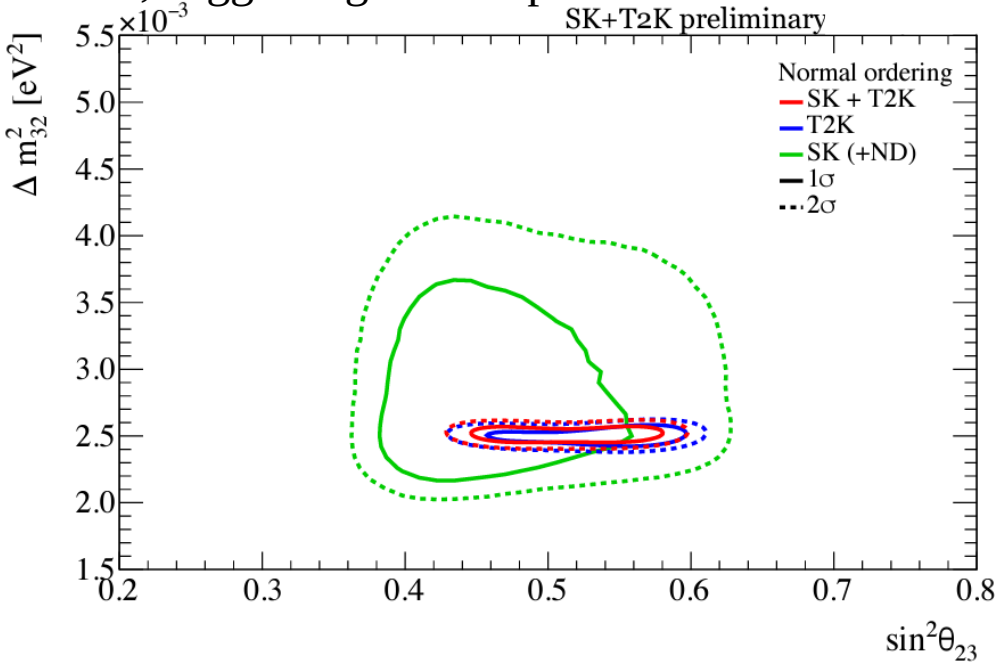
Bayesian results

- The constraint of the joint SK-T2K data is mainly from the T2K samples. Combined with the Super-K samples, the constraint becomes stronger than in the individual T2K-only fit.

- T2K-only data fit shows a preference for the upper octant, while the Super-K-only data fit shows a preference for the lower octant. When the data from both experiments are combined, the results does not have a strong octant preference.

- MO Bayes factor = P(NO)/P(IO) in this joint analysis is ~9, suggesting a week preference for normal MO.





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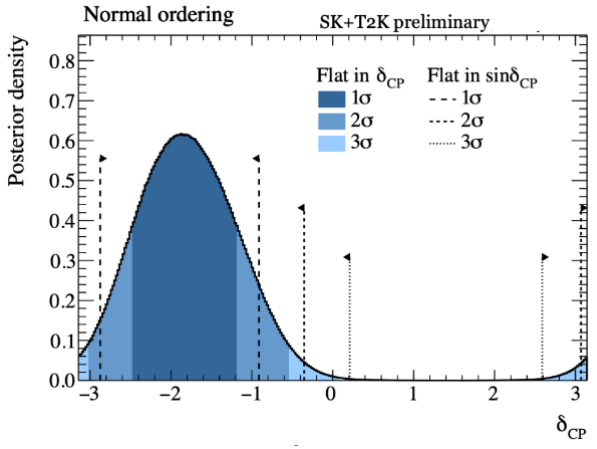
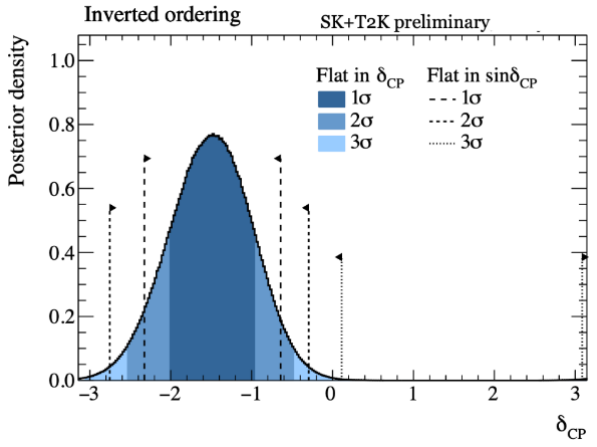
A. Eguchi@NNN2023

δ_{CP} credible interval and Jarlskog invariant intervals

- $\delta_{CP} = 0$ or π is excluded by 2σ with a flat δ_{CP} prior.
- However, $\delta_{CP} = \pi$ is not excluded at the 2σ level in normal MO with a flat $\sin\delta_{CP}$ prior.

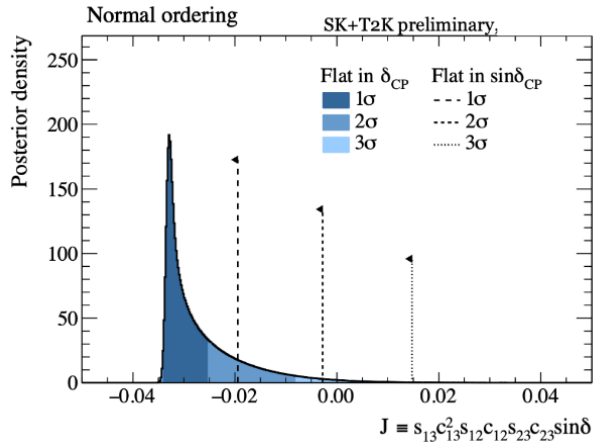


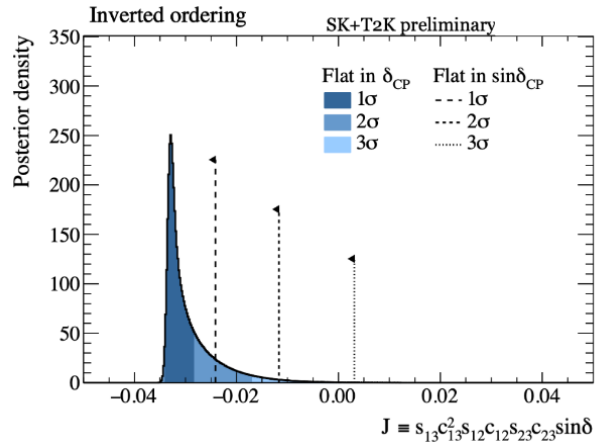


Jarlskog invariant credible intervals

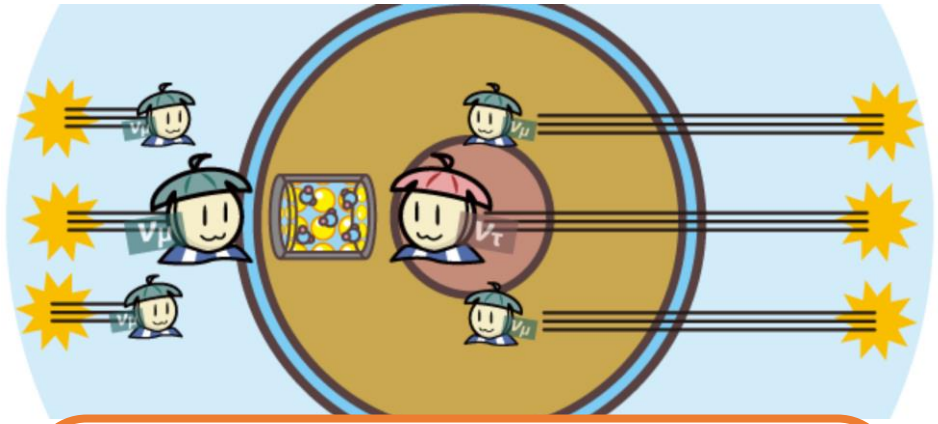
$$J_{CP} = s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin\delta_{CP}$$

- $J_{CP} = 0$ is excluded at 2σ with the flat δ_{CP} prior.
- The exclusion of $J_{CP} = 0$ at 2σ is not robust with respect to possible biases seen in studies of alternative models for the flat prior of $\sin\delta_{CP}$





Summary



Atmospheric neutrinos

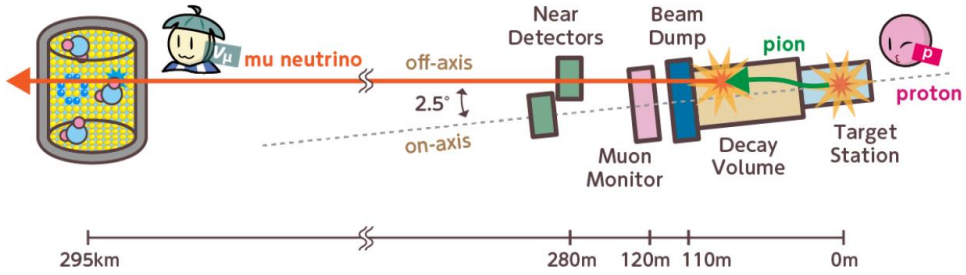
- Sensitive to MO

SK-T2K joint analysis
is able to improve sensitivity by resolving the degenerate effect from neutrino oscillation parameters

Assume data taking will continue until the end of 2027

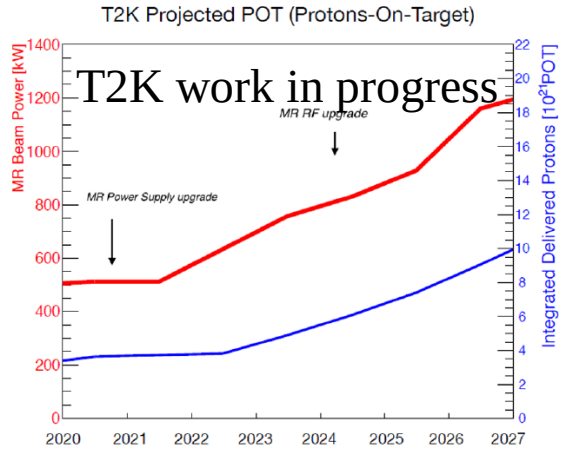
2 times as much SK data, new samples and event selections at both detectors…

Second iteration is now starting!



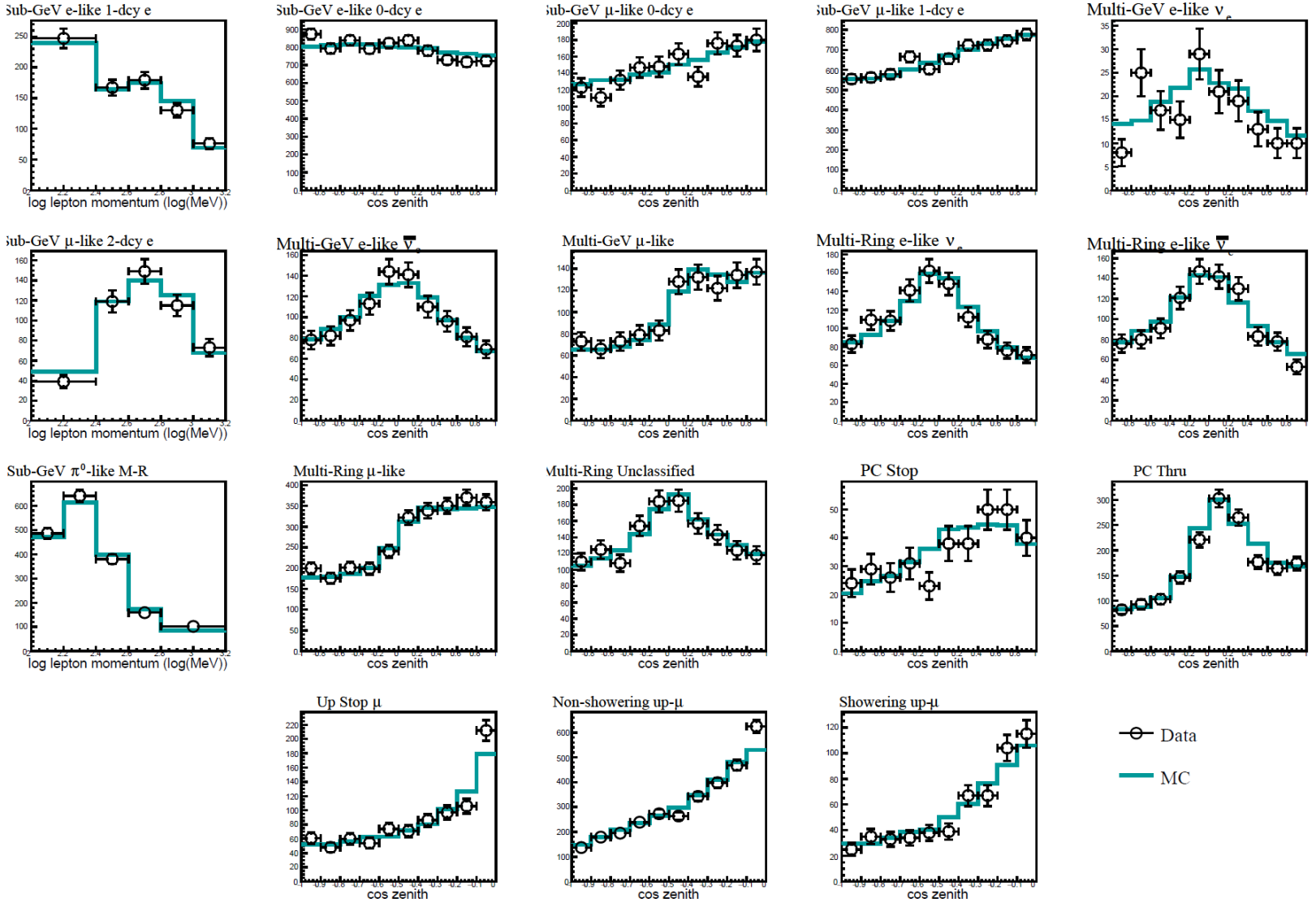
Accelerator neutrinos

- Sensitive to CP-violation phase



Backup

Data and MC comparisons for the joint SK-T2K data (atmospheric samples)



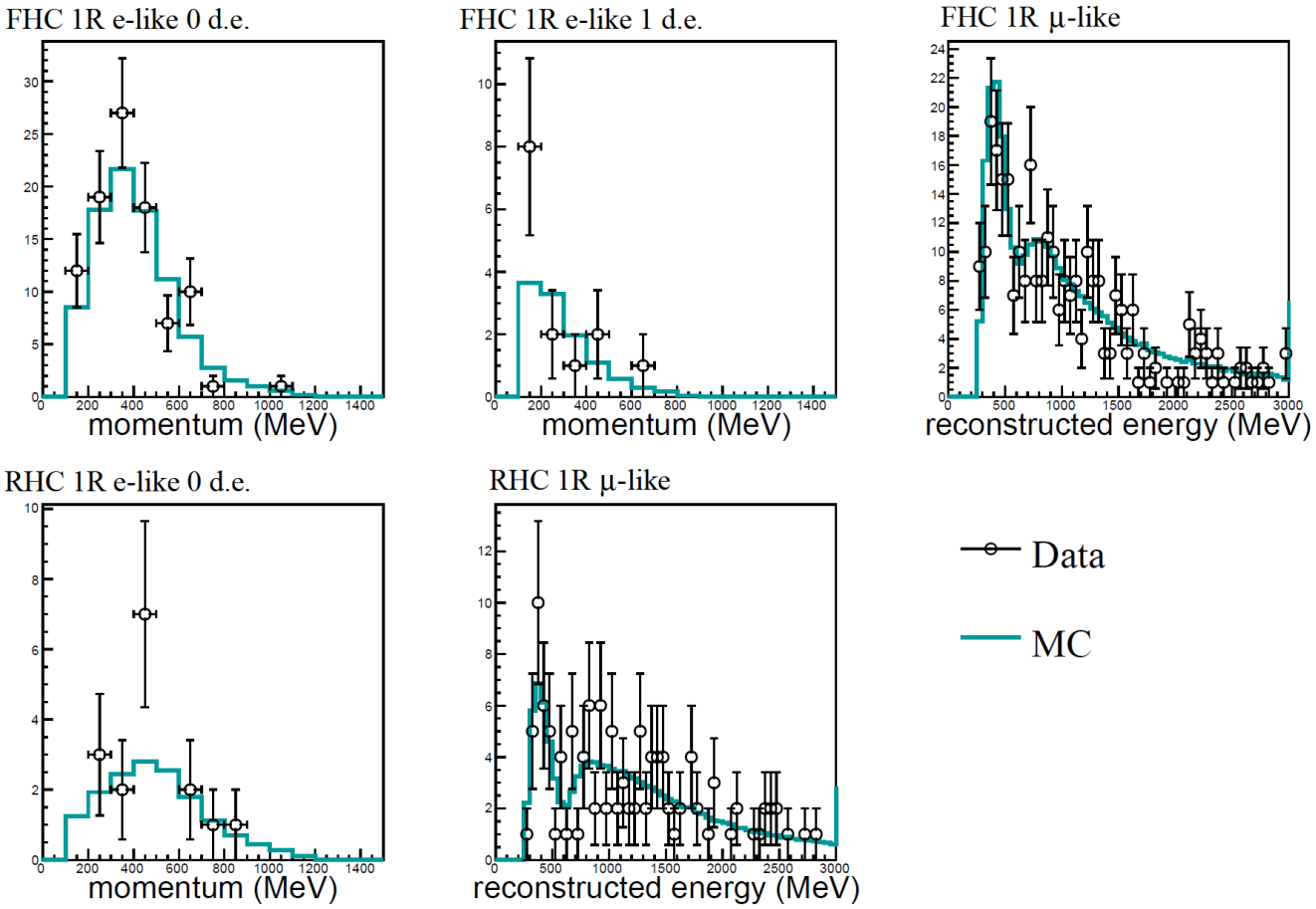
- The predicted MC is at the best-fit point of the Joint SK+T2K fit.

- Data and MC comparison for the SK data (Super-K phase IV) divided into 18 samples.

- Samples with one zenith angle bin are shown as reconstructed momentum distributions (first column)

- Others are shown as zenith angle distributions (second through fifth column)

Data and MC comparisons for the joint SK-T2K data (beam samples)



- Data and MC comparison for the T2K data (T2K run 1-10) divided into 5 samples.