京都大学
KYOTO UNIVERSITY

Neutrino Oscillation Analysis with Combined Data from Super-Kamiokande and T2K

Jianrun Hu (Kyoto University)
On Behalf of the SuperK and T2K Collaborations

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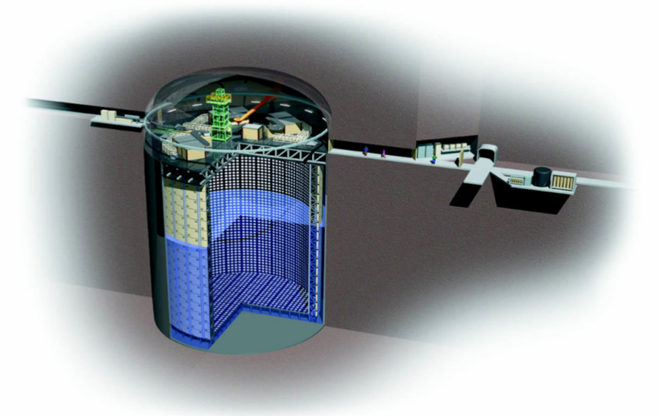
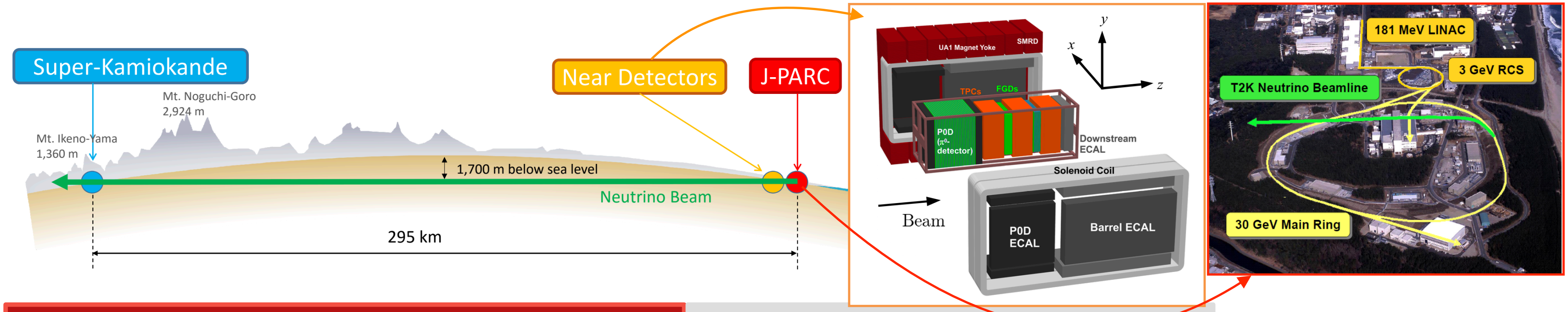
Experiments

- Super-Kamiokande (SK) experiment: 50 kton water Cherenkov detector located in Gifu, Japan.
  - Measure atmospheric neutrinos (wide ranges of E_ν and L).
  - Good separation of e and μ.
  - Cannot separate ν and $\bar{\nu}$ event-by-event.



- Tokai-to-Kamioka (T2K) experiment: a long baseline ($L \simeq 295$ km) neutrino oscillation experiment in Japan.
  - Primary $\nu_\mu/\bar{\nu}_\mu$ beam ($E_\nu \simeq 0.6$ GeV) produced at the J-PARC.
  - Near detector ND280 is used to constrain cross-section and flux models.
  - SK is used as far detector to measure neutrino after oscillation.

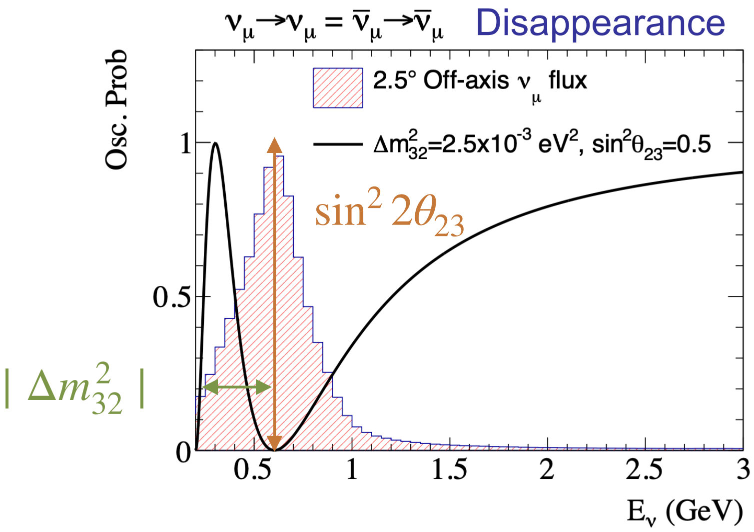


hu.jianrun.7d@kyoto-u.ac.jp (Kyoto U.)

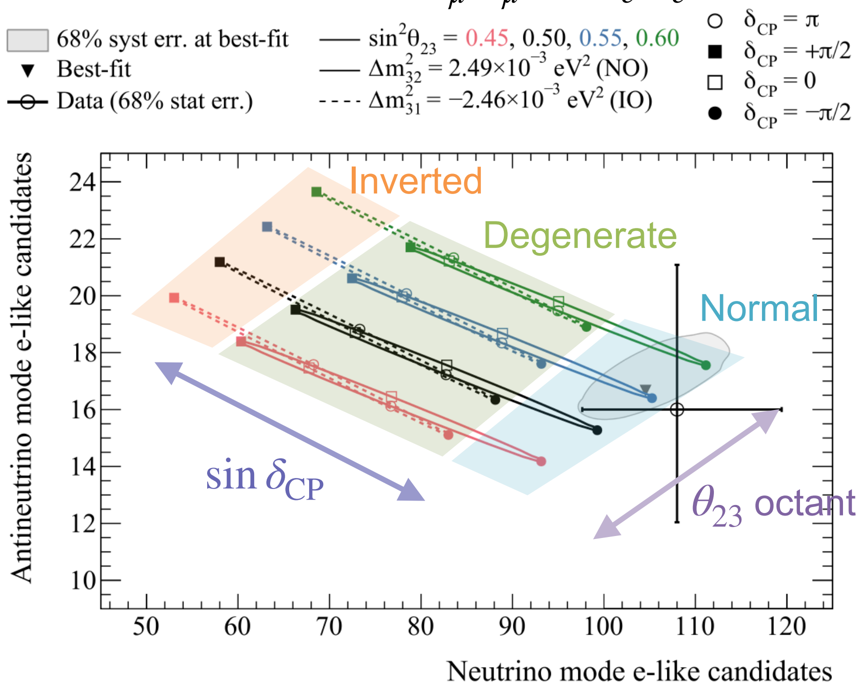
arXiv:2405.12488

Oscillation in T2K

- T2K measures both the appearance $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ and disappearance $\nu_\mu(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu)$ probabilities using almost pure flux.
  - Disappearance channels sensitive to $\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$.
  - Appearance channels sensitive to δ_{CP}, θ_{23} octant, and sign of Δm^2_{32} (neutrino mass ordering, MO).
- Due to weak matter effect, δ_{CP} has large area of degenerate phase space with MO.



Appearance $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$



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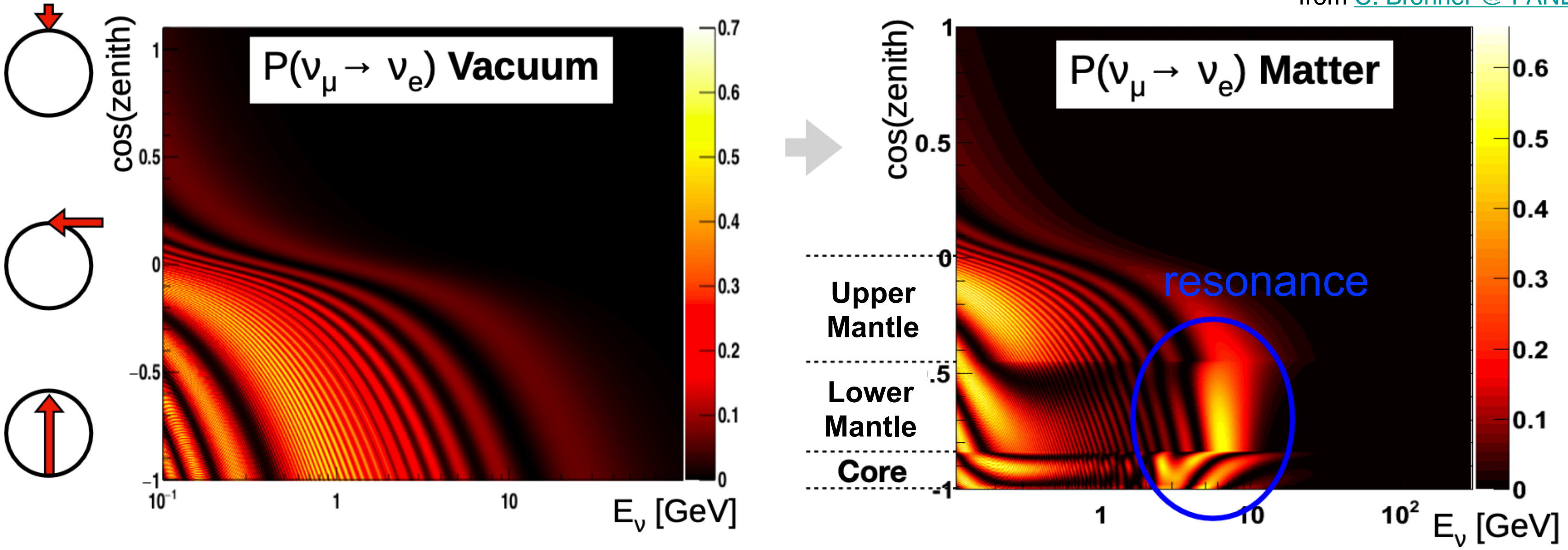
Oscillation in SK

- SK has stronger discrimination of the mass ordering thanks to the presence of a resonance driven by θ_{13}-induced matter effects between 2 and 10 GeV.
  - Only for ν in NH; only for $\bar{\nu}$ in IH.
  - Size of the effect depends on $\sin^2\theta_{23} \rightarrow$ sensitive to θ_{23} octant.
- Some sensitivity to $\delta_{\rm CP}$ from sub-GeV e-like events.

Atmospheric neutrino oscillation probability (normal ordering)

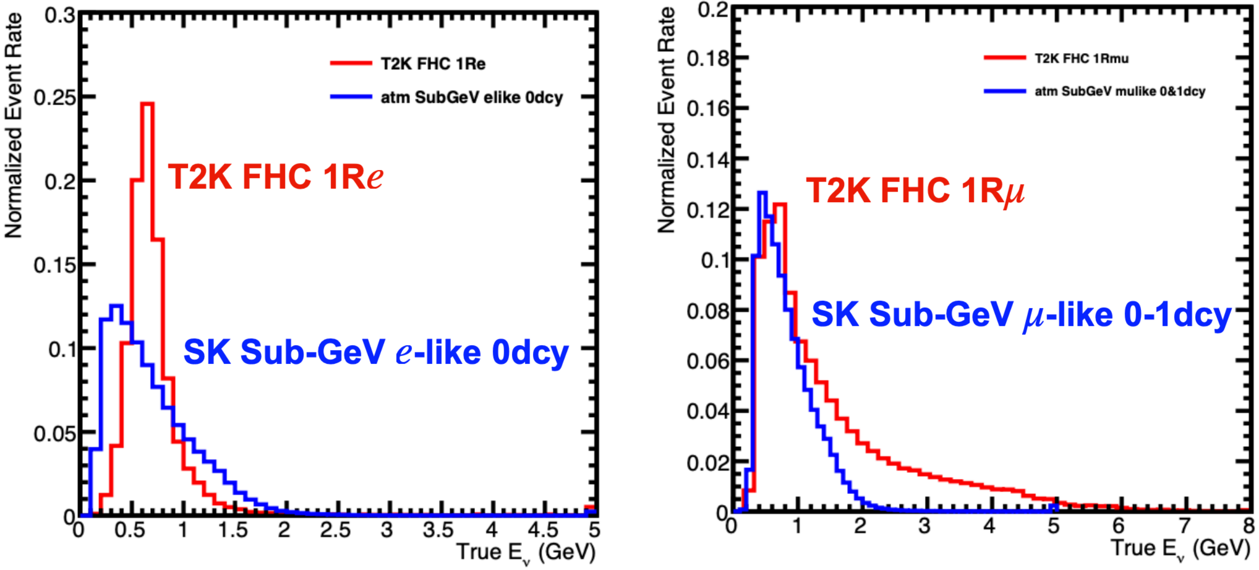
from C. Bronner @ PANE 2018



Motivation of Joint Analysis

- Combining these two experiments → expect to get better sensitivity to oscillation parameters and mass ordering with increased statistics.
  - SK helps to break the **degeneracy between δ_{CP} and mass ordering** in T2K.
  - T2K can constrain $\sin^2\theta_{23}$ better → improve the mass ordering sensitivity in SK.
- T2K and SK have samples with similar energy ranges:
  - T2K near detector can be used to constrain the cross-section uncertainties for the low-energy atmospheric samples.

Comparison of the normalized flux of the selected samples



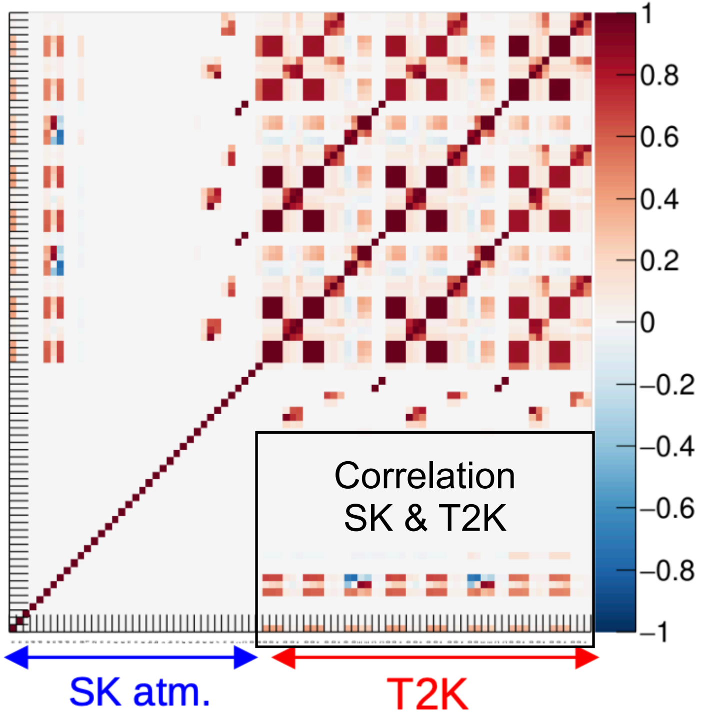
Cross Section & Detector Models

- Develop unified interaction model for T2K beam and SK low-energy samples.
  - High energy: modified SK model including additional systematics uncertainties
- The same detector/simulation software/reconstruction tool is used for the samples of both experiments.
  - Correlations of detector systematics included.

Cross section models

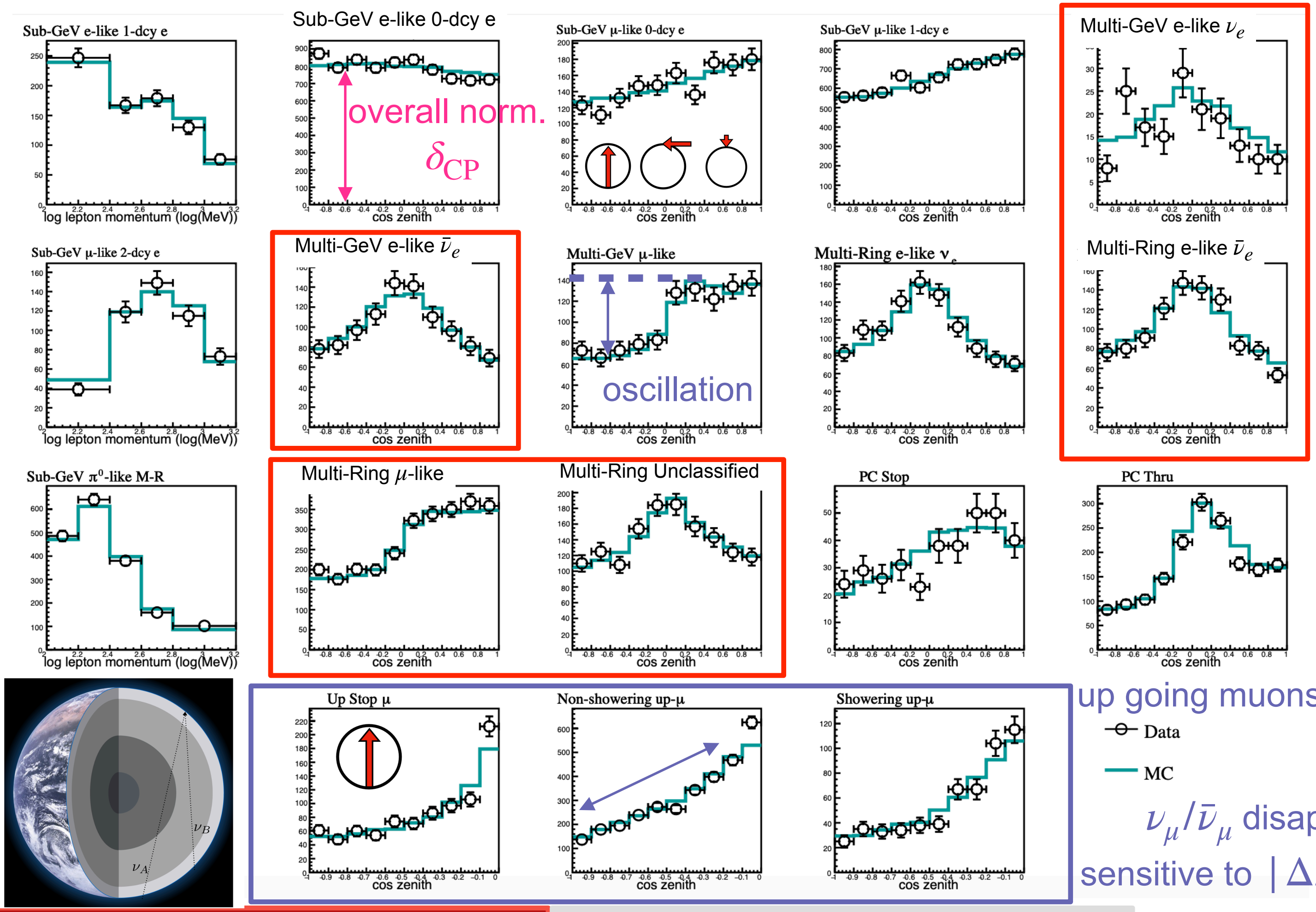
	Low-energy sub-GeV atm + beam	**High-energy** multi-GeV atm
CCQE	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	add ν_e/ν_μ ratio unc. (CRPA)	
2p2h	T2K model w/ND280	SK model (100% error) + T2K-style shape
Resonant	T2K model w/ND280 + new pion momentum dial + NC1π0 uncertainties	SK model for 3 dials common with T2K, use more recent larger T2K priors
DIS	T2K model w/ND280	SK model
ν_τ	SK model (25% norm on top of other syst) for other systematics checked that we have no numerically unstable values	
FSI	T2K model w/ND280	T2K model w/o ND280 should be mostly same as SK model
SI	T2K model, correlated in low-E/high-E only applied to FC and PC for atm, PN not applied to atm	

Correlated detector systematics



Samples & Best-fit (SK)

- 18 SK atmospheric samples with 3244.4 days of data taking
- Described in [PTEP 2019 (2019) 5, 053F01]



Multi-GeV samples: sensitive to mass ordering & θ_{23} octant through matter effect

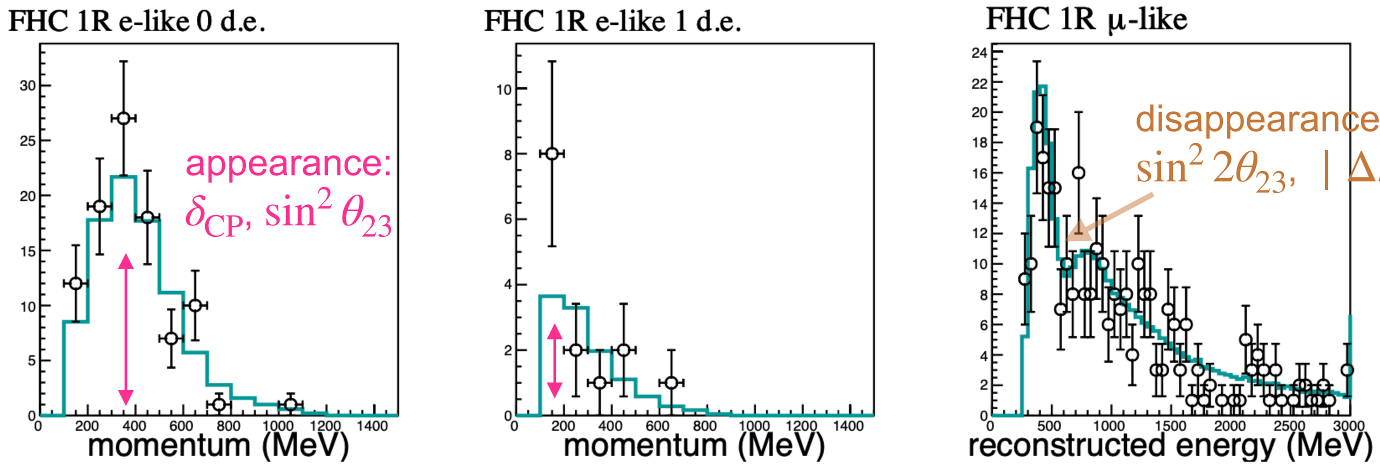
up going muons

$\nu_\mu/\bar{\nu}_\mu$ disappearance: sensitive to $|\Delta m^2|$, $\sin^2 2\theta_{23}$

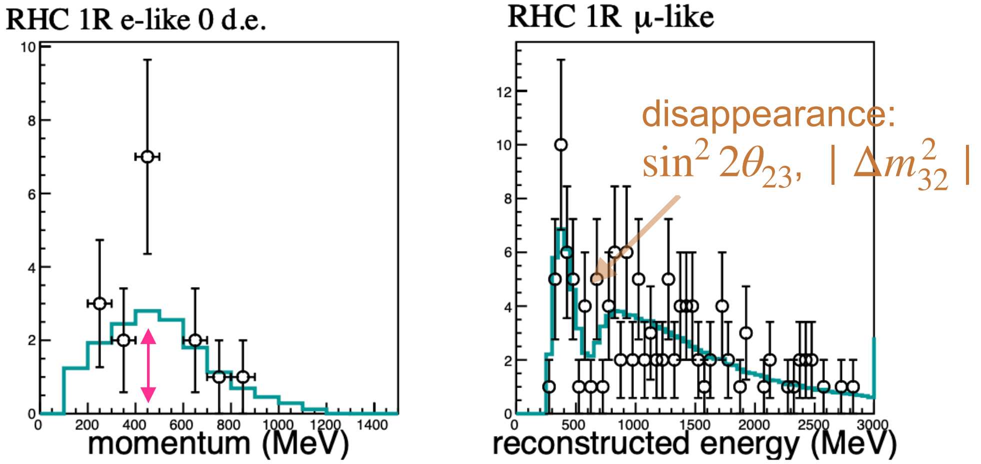
Samples & Best-fit (T2K)

- 5 T2K beam samples with $19.7(16.3) \times 10^{20}$ POT in (anti-)neutrino mode
- Described in [Eur.Phys.J.C 83 (2023) 9, 782]

FHC:
ν mode



RHC:
$\bar{\nu}$ mode

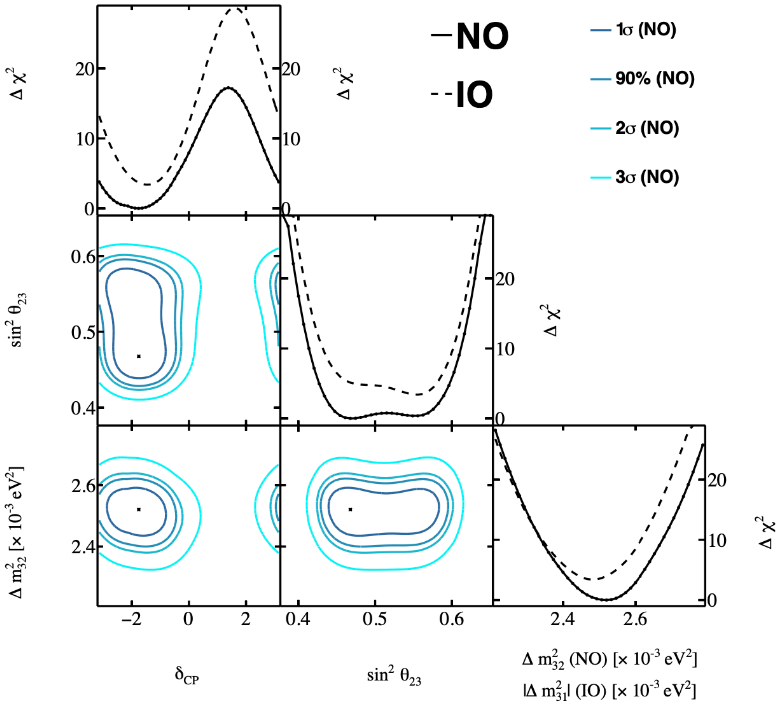


Good consistency between the atmospheric and beam samples (p=0.24 in Frequentist test).

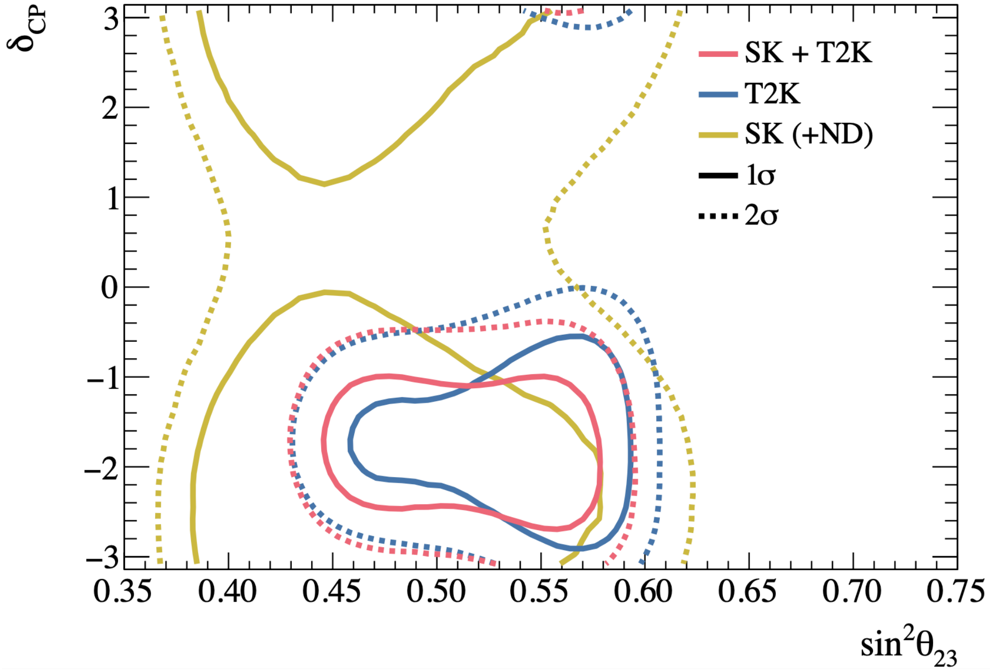
Fitting Results

- Frequentist: obtain $\Delta\chi^2$ distributions profiling the systematic errors.
- Bayesian: constructed Bayesian credible intervals from the posterior probability distributions.
  - The constraints are largely dominated by T2K but SK also has a significant contribution on the octant and MO (frequentist in backup).

$\Delta\chi^2$ distributions of SK+T2K frequentist analysis



$(\sin^2\theta_{23}, \delta_{CP})$ Bayesian credible regions

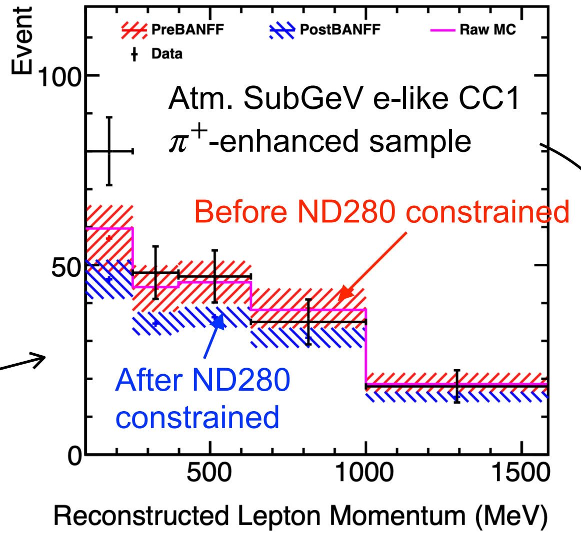


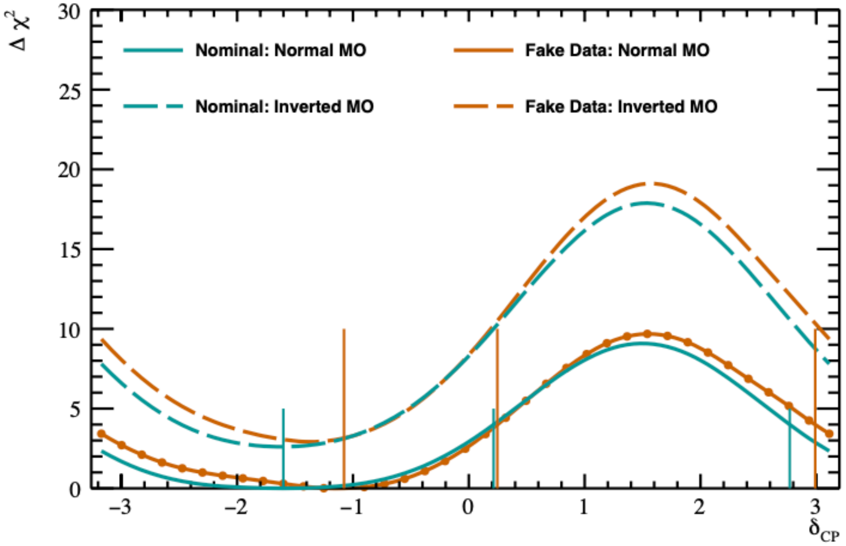
hu.jianrun.7d@kyoto-u.ac.jp (Kyoto U.)

arXiv:2405.12488

Robustness Studies

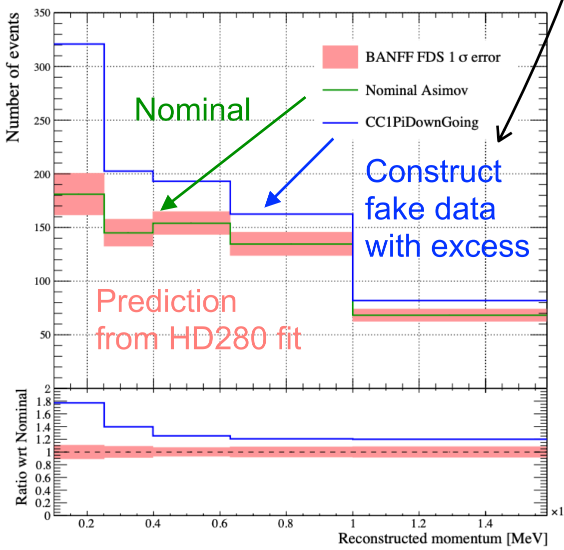
- Estimate potential biases from some possible weaknesses of our model.
- Test 14 alternative models and data-driven effects in simulated data to estimate biases.
  - Δm^2_{32} is smeared by convolving with gaussian representing the biases.
- Example: Excess observed in down-going atmospheric data aggravated by T2K ND.





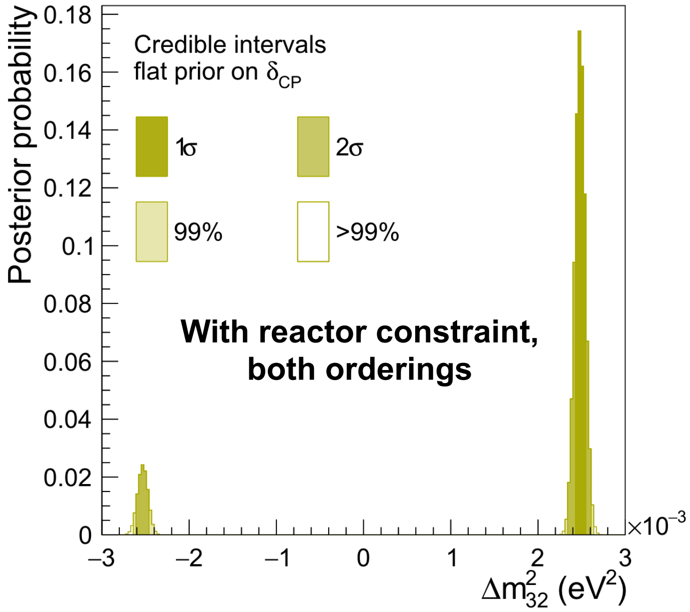
Evaluate the effect using difference between nominal fit and simulated data fit results.

Apply the difference to data results → effect on intervals & p-values.

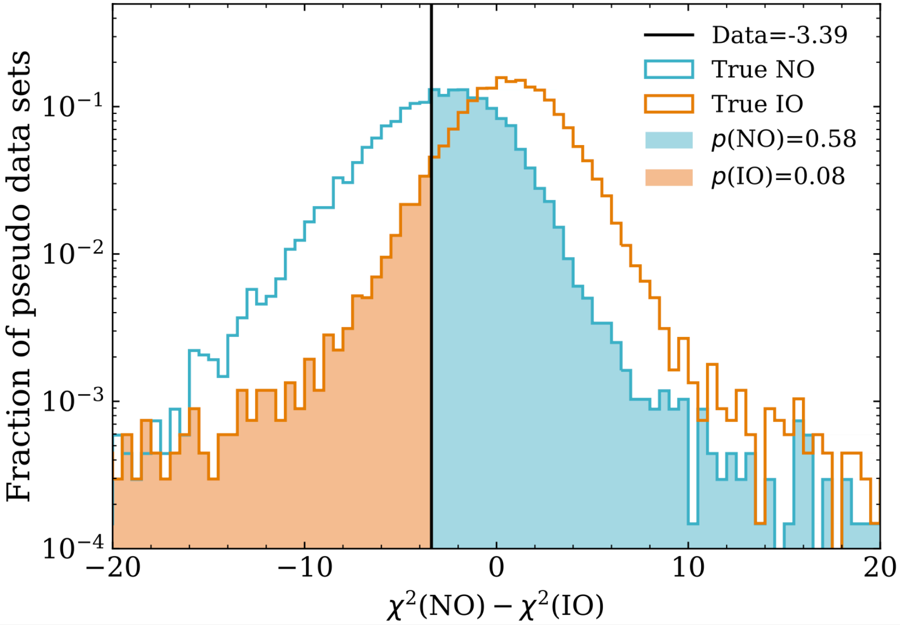


Mass ordering

- Bayesian: mass ordering posterior probability for NO is ~0.9, corresponds to the probability of obtaining a ~1.64σ deviation assuming IO in a Gaussian assuming equal prior probabilities.
- Frequentist: with ensembles of constructed pseudo-experiments, weak rejection of IO with $p(\mathrm{IO}) = 0.08$ ($\mathrm{CLs} = \mathrm{p(IO)}/(1 - \mathrm{p(NO)}) = 0.18$).
- Potential biases in robustness studies are small (0.001 change on $p(\mathrm{IO})$).
- Conclusion: **a limited** preference (~90% C.L.) for **normal ordering**.



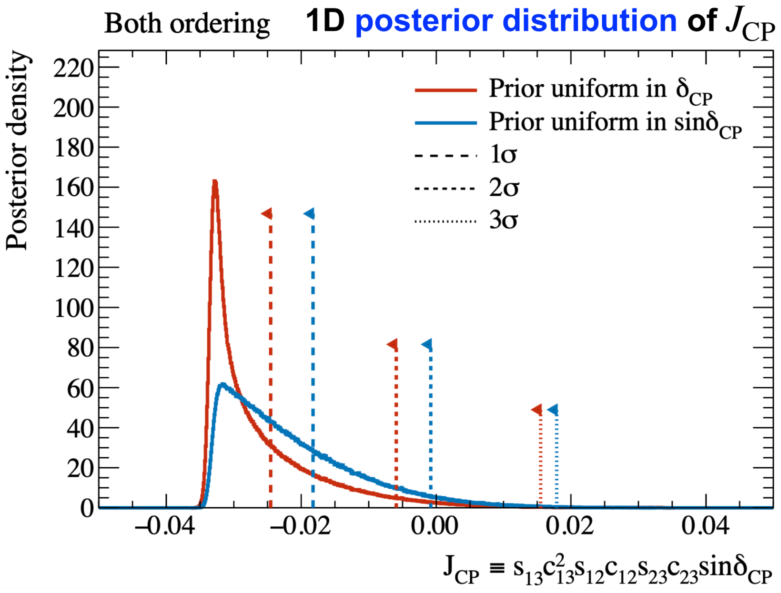
1D posterior distribution of Δm^2_{32}



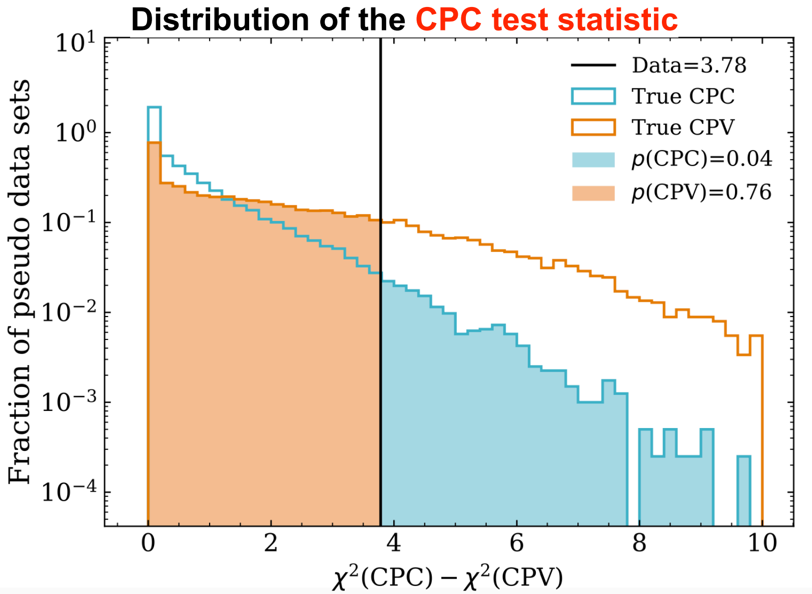
Distribution of the MO test statistic

CP Violation

- **Bayesian**: The exclusion of the CP conserving values of Jarlskog invariant $J_{\mathrm{CP}} = 0$ is 2.2σ (1.9σ) for flat δ_{CP} ($\sin\delta_{\mathrm{CP}}$) prior.
- **Frequentist**: p-value of CP-conservation ($\sin\delta_{\mathrm{CP}} = 0$) is about 0.04 (2$\sigma$ exclusion), but increases to 0.05 after considering possible bias from CC1π down-going excess.
- Good agreement (p=0.75) with an alternative hypothesis "Posterior δ_{CP} ".
- Conclusion: slightly **< 2σ exclusion of CP conservation**.



Both ordering **1D posterior distribution of J_{CP}**

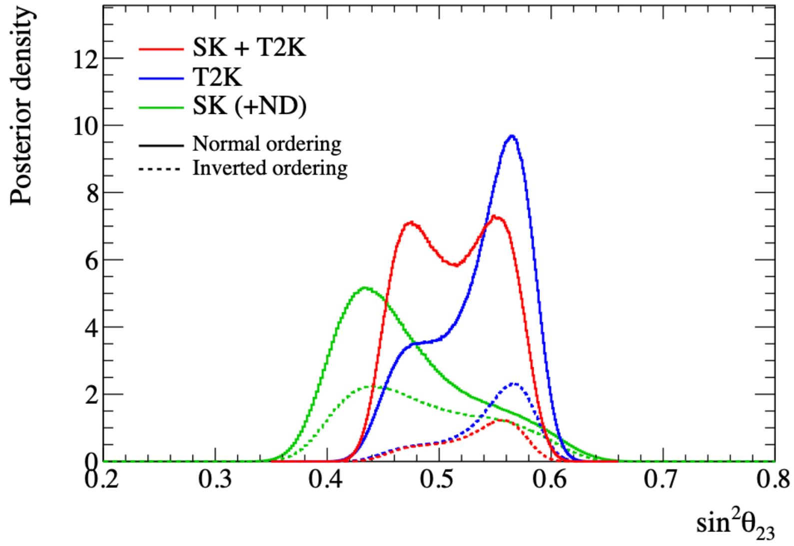


Distribution of the CPC test statistic

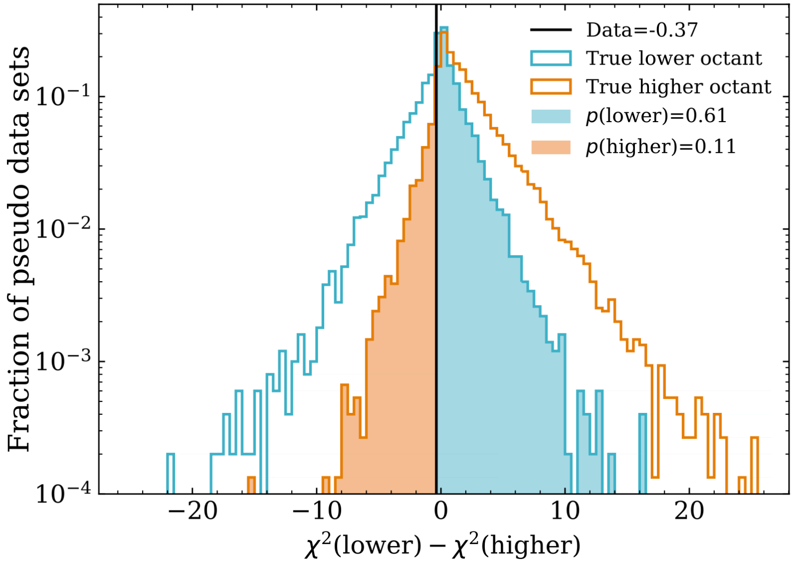
θ_{23} Octant

- Different octant preference by each experiment.
- Combined analysis: Bayesian posterior probability prefers upper octant while $\Delta\chi^2$ of the best-fit value prefer lower octant.
- Bayesian: upper octant posterior probability is 0.64 → ~0.9σ deviation of lower octant.
- Frequentist: $\Delta\chi^2$ is only -0.37, but p-value (CLs) for the higher θ_{23} octant is 0.11 (0.28).
- Conclusion: **no obvious** preference on the octant.

1D posterior distribution of $\sin^2\theta_{23}$



Distribution of the θ_{23} Octant test statistic



hu.jianrun.7d@kyoto-u.ac.jp (Kyoto U.)

arXiv:2405.12488

Summary

- First joint oscillation analysis of SK atmospheric + T2K accelerator neutrino has been performed.
- Both Bayesian and frequentist analyses are performed with additional robustness studies.
  - A limited rejection of IO at 90% C.L..
  - CPC rejected at slightly below 2σ.
  - No preference on the θ_{23} octant.
- Potential for more sensitive combined analyses between T2K and SK.
  - SK4 (3244.4 days) → SK1-5 (6511.3 days);
  - T2K run1-10 → T2K run 1-11 (9% POT increase on FHC mode);
  - Move to latest flux and interaction models, potential additional samples.
- An important step towards the combined beam and atmospheric data analyses planned by next generation neutrino oscillation experiments.
  - Combined beam and atmospheric data analysis in HyperK.

Results released in arXiv now

⇩

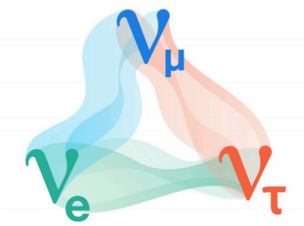
hu.jianrun.7d@kyoto-u.ac.jp (Kyoto U.)

arXiv:2405.12488

Back up

Neutrino Oscillation

- Flavor of neutrino $(\nu_e, \nu_\mu, \nu_\tau)$ changes periodically as it propagates.
- Described by mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$, mass squared differences $(\Delta M^2_{32}, \Delta M^2_{21})$, and CP phase δ_{CP}.



Flavor Eigenstates

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

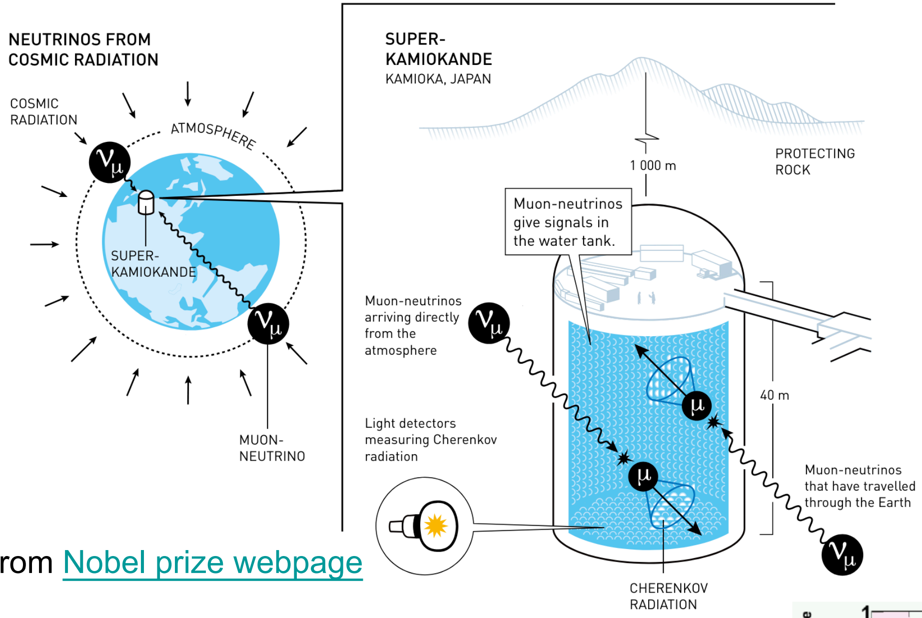
PMNS Matrix

Mass Eigenstates

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

Measurement:	$\theta_{12} \sim 34^\circ$	$\theta_{13} \sim 8.5^\circ$	$\theta_{23} \sim 45^\circ$
Precision:	$\sin^2\theta_{12} \sim 4\,\%$	$\sin^2\theta_{13} \sim 3\,\%$	$\sin^2\theta_{23} \sim 5\,\%$

Neutrino Oscillation at SK



from [Nobel prize webpage]

$$P(\nu_e \to \nu_e) \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m^2_{31} L}{E}\right)$$

$$P(\nu_\mu \to \nu_\mu) \cong 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23}) \times \sin^2\left(\frac{1.27\Delta m^2_{31} L}{E}\right)$$

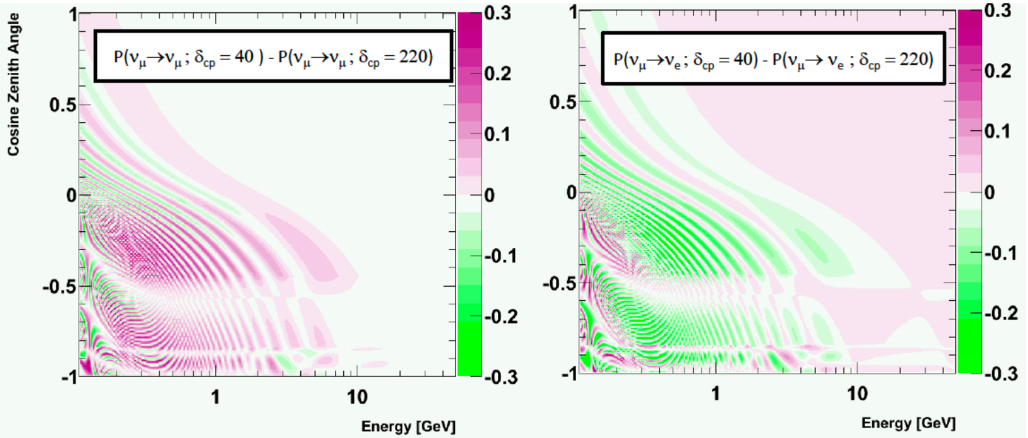
$$P(\nu_\mu \leftrightarrow \nu_e) \cong \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{31} L}{E}\right). \qquad (4)$$

Matter effect:

$$\Delta m^2_{31,M} = \Delta m^2_{31}\sqrt{\sin^2 2\theta_{13} + \left(aE/\Delta m^2_{31} - \cos 2\theta_{13}\right)^2}$$

$$\sin^2 2\theta^M_{13} = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left(aE/\Delta m^2_{31} - \cos 2\theta_{13}\right)^2}$$

- Given neutrino flux and detector energy and angular resolution, sensitivity mainly comes from number of sub-GeV e-like events
- More ν_e appearance events for $\delta_{\mathrm{CP}} \sim 220 - 240°$, and less for $\delta_{\mathrm{CP}} \sim 40 - 45°$



from [C. Bronner @ PANE 2018]

Neutrino Oscillation at T2K

- The goal of Long Baseline neutrino experiments:
  - ✓ Remaining problems: CP symmetry, Mass ordering, Octant of θ_{23}
  - ✓ Precise measurements of $\theta_{23}, |\Delta m^2{}_{31}| \, (\sim |\Delta m^2{}_{32}|)$

- **Muon neutrino disappearance ($\nu_\mu \to \nu_\mu$) :**

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \left(\cos^2\theta_{13}\sin^2 2\theta_{23}\right)\sin^2\left(\Delta m^2_{32}\frac{L}{4E_\nu}\right)$$

Sensitive to:

$\theta_{23}, \left|\Delta m^2{}_{31}\right| \left(\sim \left|\Delta m^2{}_{32}\right| \right)$

- **Electron neutrino appearance ($\nu_\mu \to \nu_e$) :**

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}\left(1-2\sin^2\theta_{13}\right)\right)$$

$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

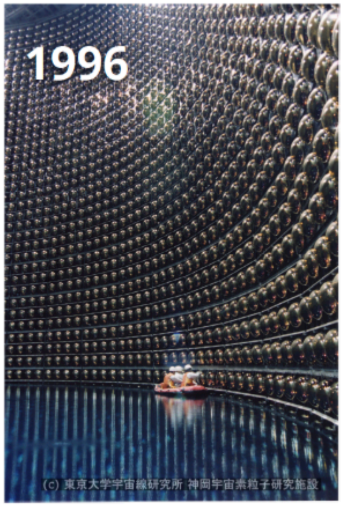
Sensitive to:

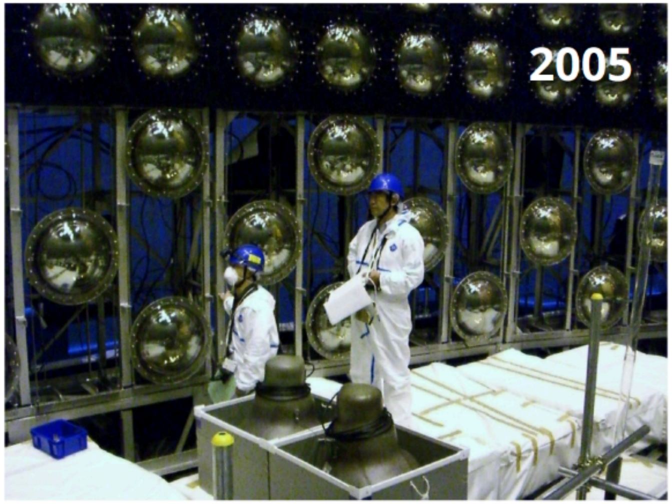
$\theta_{13}, \delta_{CP}, \theta_{23}$, and

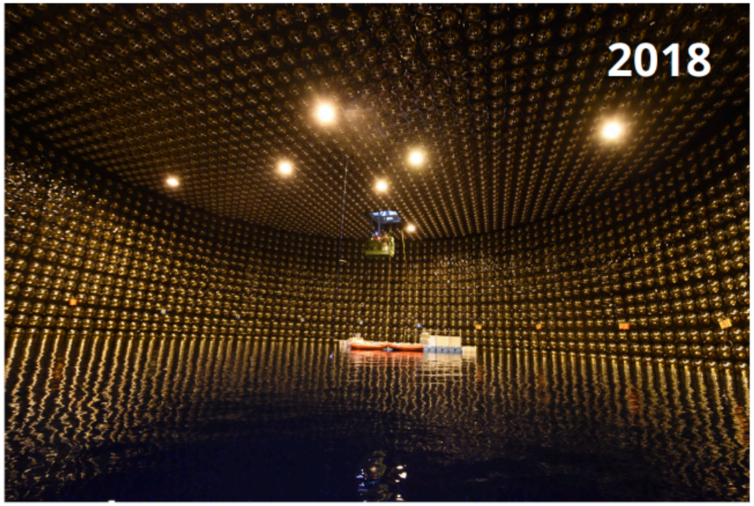
Mass ordering $\Delta m^2{}_{31}$

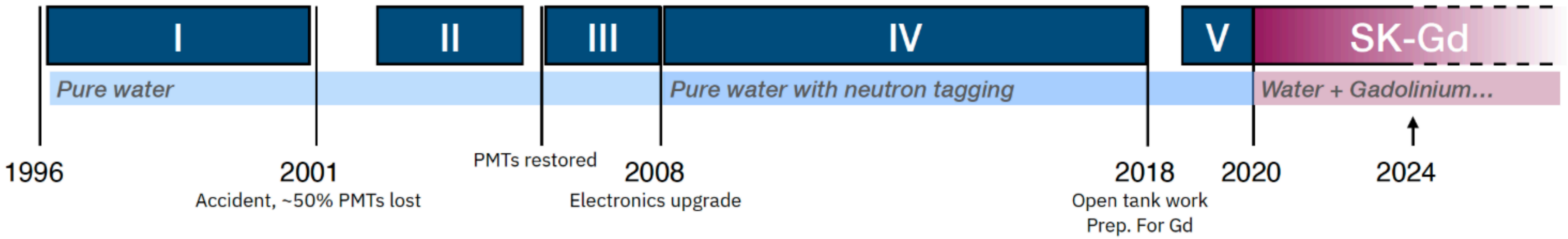
- **$P(\bar{\nu}_\mu \to \bar{\nu}_e)$: δ turns into – δ and a to -a (“a” matter effect term)**

SK Periods









1482 dys	798 dys	518 dys	3244.4 dy	461 dy	564.4 SK6 0.01% Gd	—- SK7 0.03% Gd

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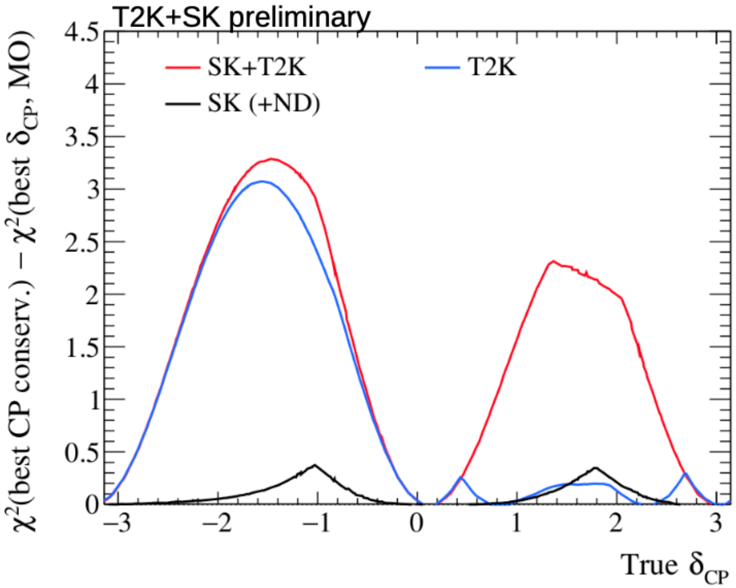
arXiv:2405.12488

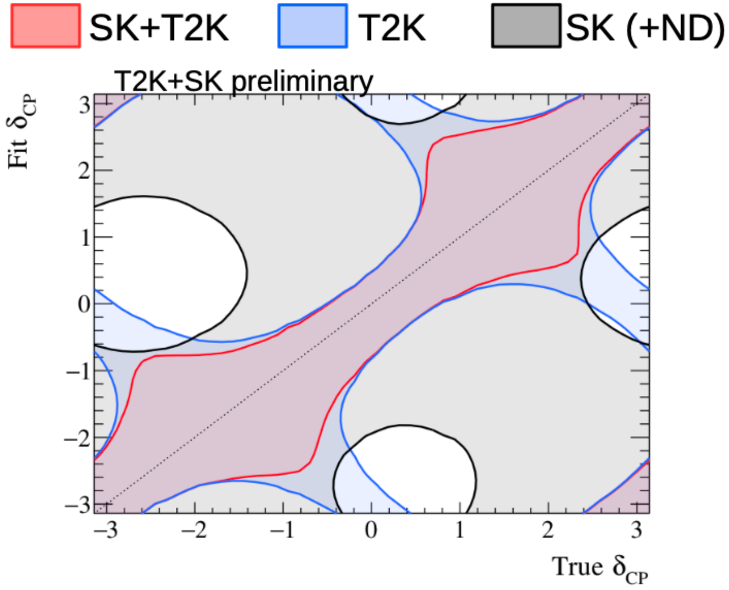
Joint Analysis Sensitivity

- Sensitivity to δ_{CP} dominated by T2K
- Joint fit allows to break degeneracy with cos(δ_{CP}) and mass ordering

Ability to exclude CP conservation as a function of true δ_{CP} assumed



68% CL intervals for δ_{CP} as a function of true δ_{CP} assumed



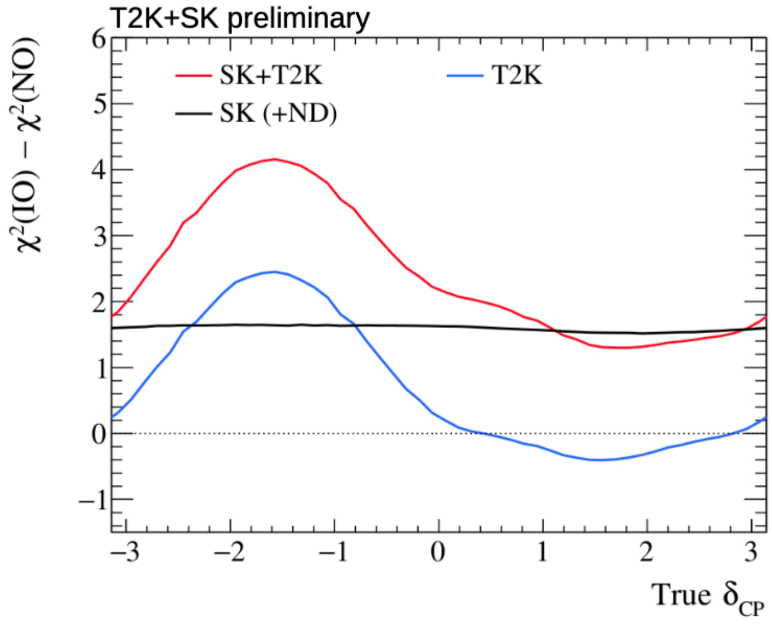
"SK (+ND)": T2K ND constraint on interaction uncertainties used for low E atmospheric samples
True values assumed: $\sin^2(\theta_{23})=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}$ eV^2/c^4, $\sin^2(\theta_{13})=0.0218$, NO

from C. Bronner @ Neutrino 2022

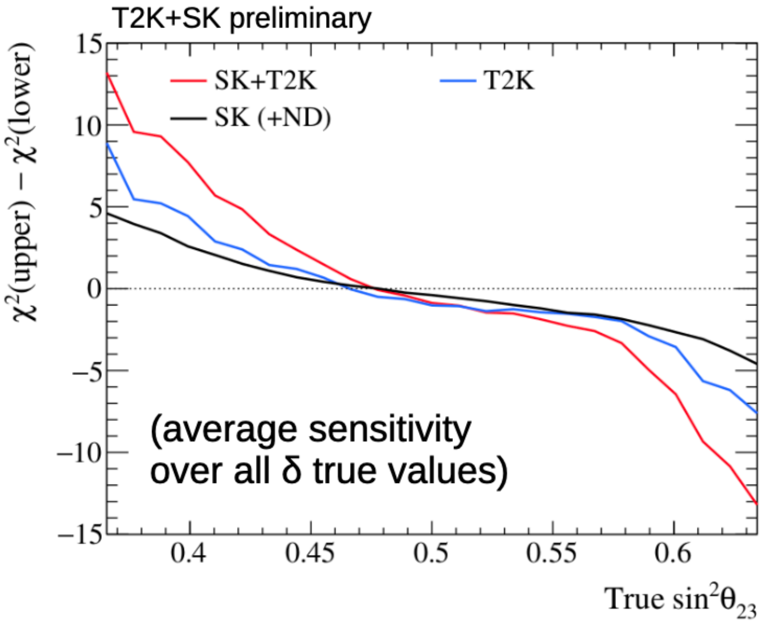
Joint Analysis Sensitivity

- For mass ordering and θ_{23} octant, more similar contributions from the two experiments, with different dependence on true values of the parameters
- Joint fit gets an increased sensitivity compared to individual experiments as a result

Ability to reject wrong mass ordering



Ability to reject wrong θ_{23} octant



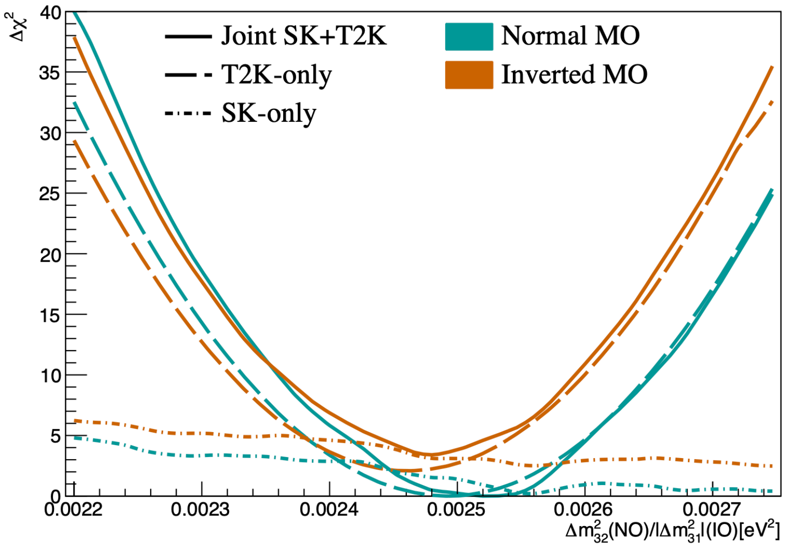
(average sensitivity over all δ true values)

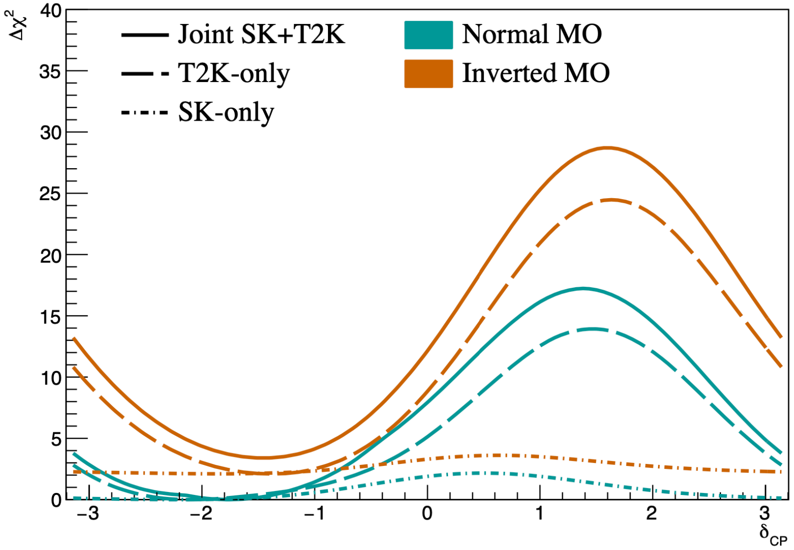
"SK (+ND)": T2K ND constraint on interaction uncertainties used for low E atmospheric samples
True values assumed: $\sin^2(\theta_{23})=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}$ eV^2/c^4, $\sin^2(\theta_{13})=0.0218$, NO

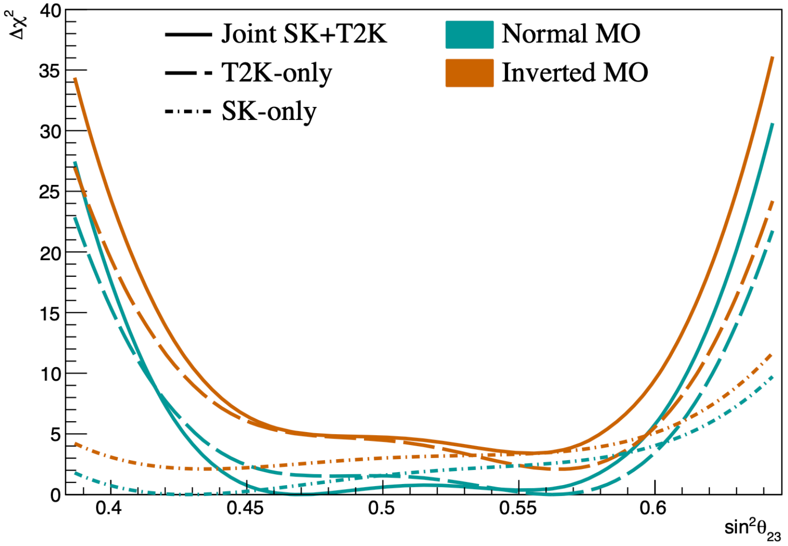
from C. Bronner @ Neutrino 2022

Joint Analysis Data Fit

- Frequentist: $\Delta\chi^2$ distributions of the joint fit and the individual experiments.
- The constraints are largely dominated by T2K but SK also has a significant contribution on the octant and MO.







Robustness Studies

- Test 14 alternative models and data-driven effects in simulated data, propagate biases to final contours.

- The first six studies are taken from Appendix B of Eur.Phys.J.C 83 (2023) 9, 782.
- Two alternative nuclear models are tested (our baseline model is SF)
  - LFG+RPA [ref]
  - HF+CRPA [ref]

SF: Spectral Function
LFG: Local Fermi Gas
RPA: Random Phase Approximation
HF: Hartree-Fock
CRPA: Continuum Random Phase Approximation

- The last six studies were included to test possible problems that would come with the joint fit.

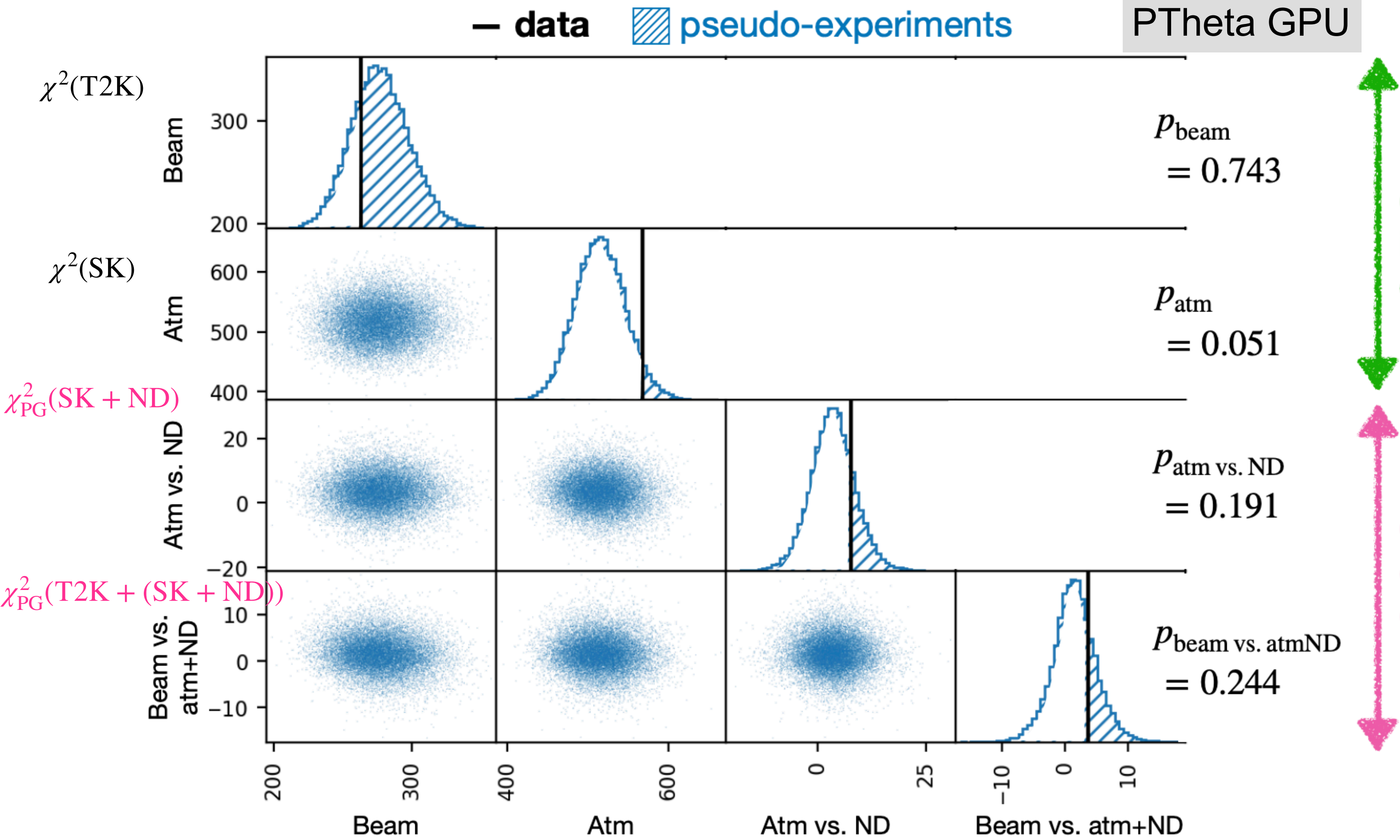
	Model component
Martini 2p2h	2p2h
ND280 data-driven pion kinematics	CC1π
CC0π non-QE alteration	CC0π
Removal energy	Nuclear Model
Axial form factors	CCQE
Pion SI bug fix	CC1π, CC$n\pi$
LFG	Nuclear model
CRPA	Nuclear model
Pion multiplicity	CC$n\pi$
Energy-dependent $\sigma_{\nu_e}/\sigma_{\nu_\mu}$	$\sigma_{\nu_e}/\sigma_{\nu_\mu}$
Xsec-only fit	Fit
Atmospheric down-going CC1π	CC1π
Atmospheric full-zenith CC1π	CC1π
No-migration energy scale fit	Fit

hu.jianrun.7d@kyoto-u.ac.jp (Kyoto U.)

arXiv:2405.12488

Goodness of Fit

Ref



Good fit of individual experiments

p_{atm} consistent with value in M. Jiang's thesis

Good consistency of data-sets

pGOF: $\chi^2_{\mathrm{PG}}(\mathrm{A+B}) = \min\{\Delta\chi^2(\mathrm{A+B})\} - \min\{\Delta\chi^2(\mathrm{A})\} - \min\{\Delta\chi^2(\mathrm{B})\}$

- Good consistency between the values of the systematic parameters favored by T2K ND and atmospheric data (p= 0.19) & atmospheric and beam samples (p=0.24).

hu.jianrun.7d@kyoto-u.ac.jp (Kyoto U.)