



京都大学
KYOTO UNIVERSITY



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

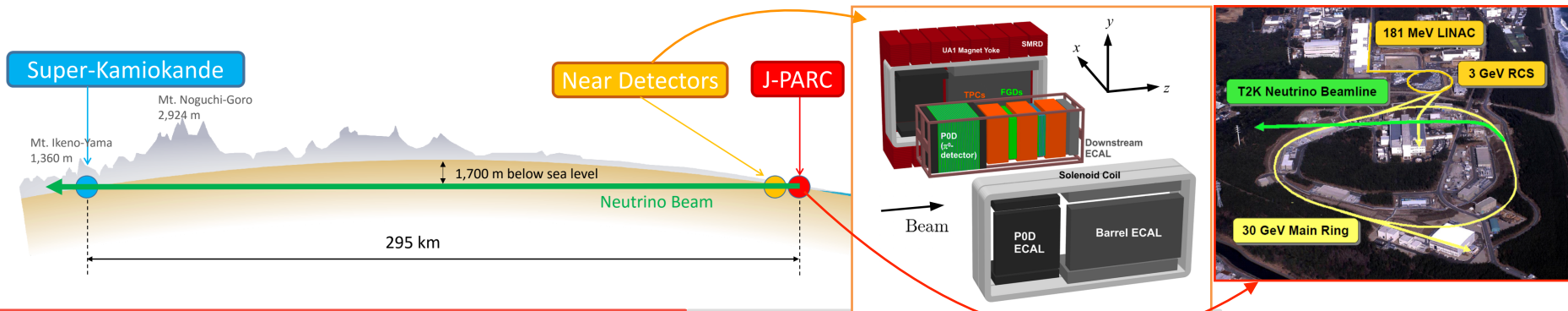
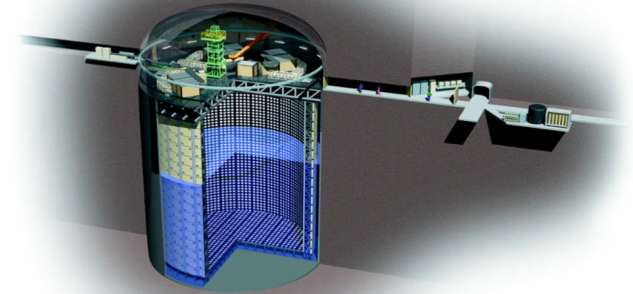
Jianrun Hu (Kyoto University)

On Behalf of the SuperK and T2K Collaborations

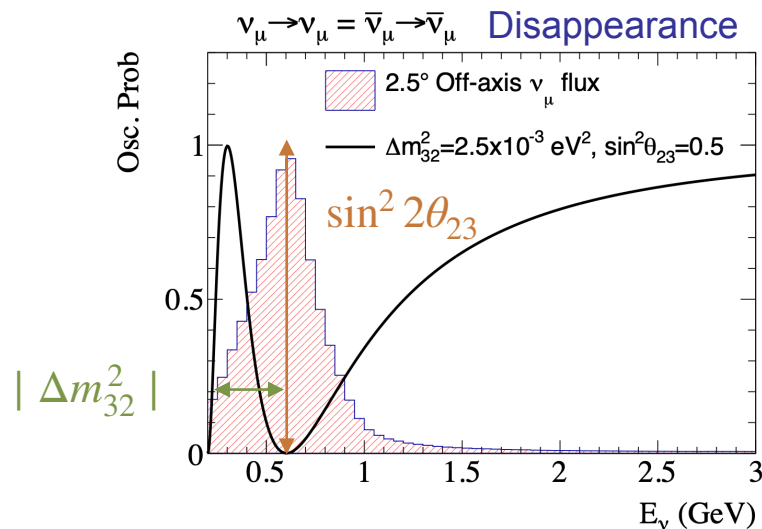
CPS 2024

Aug. 12th - Aug. 18th, 2024

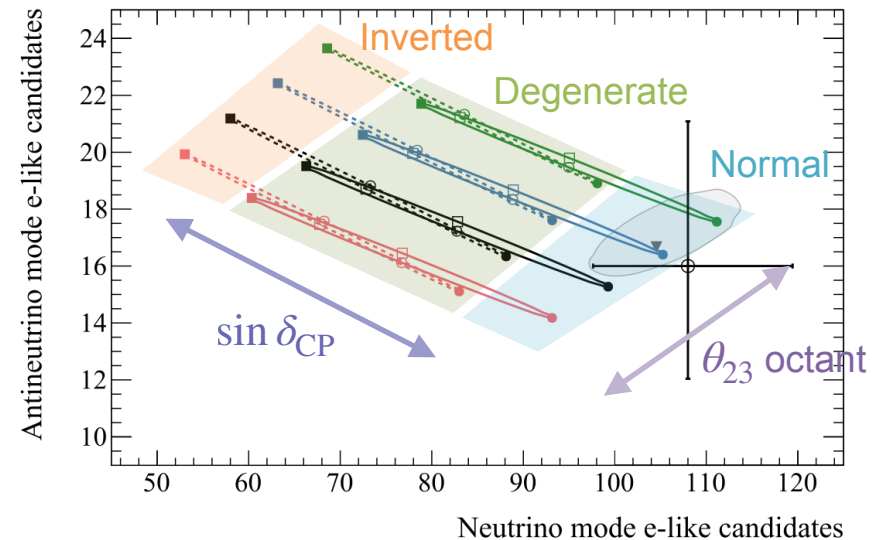
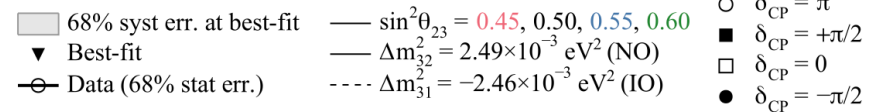
- ▶ **Super-Kamiokande (SK)** experiment: 50 kton water Cherenkov detector located in Gifu, Japan.
 - ▶ Measure atmospheric neutrinos (wide ranges of E_ν and L).
 - ▶ Good separation of e and μ .
 - ▶ Cannot separate ν and $\bar{\nu}$ event-by-event.
- ▶ **Tokai-to-Kamioka (T2K)** experiment: a long 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.



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



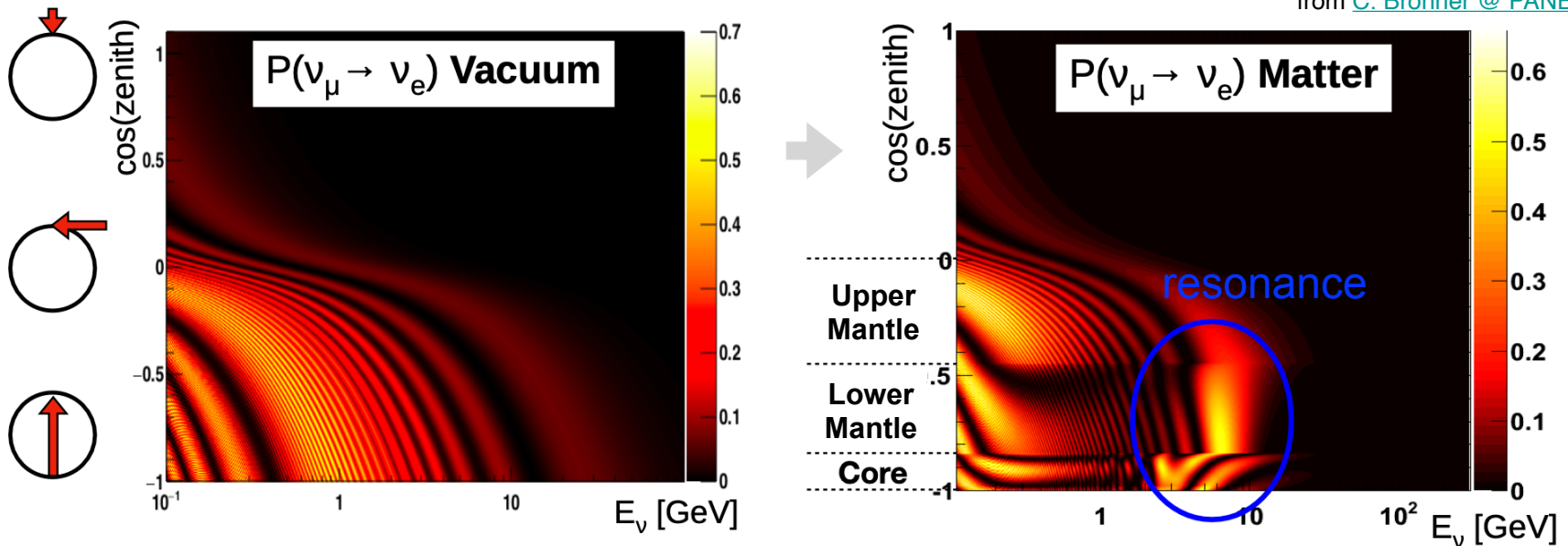
Appearance $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$



- ▶ 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 δ_{CP} from sub-GeV e-like events.

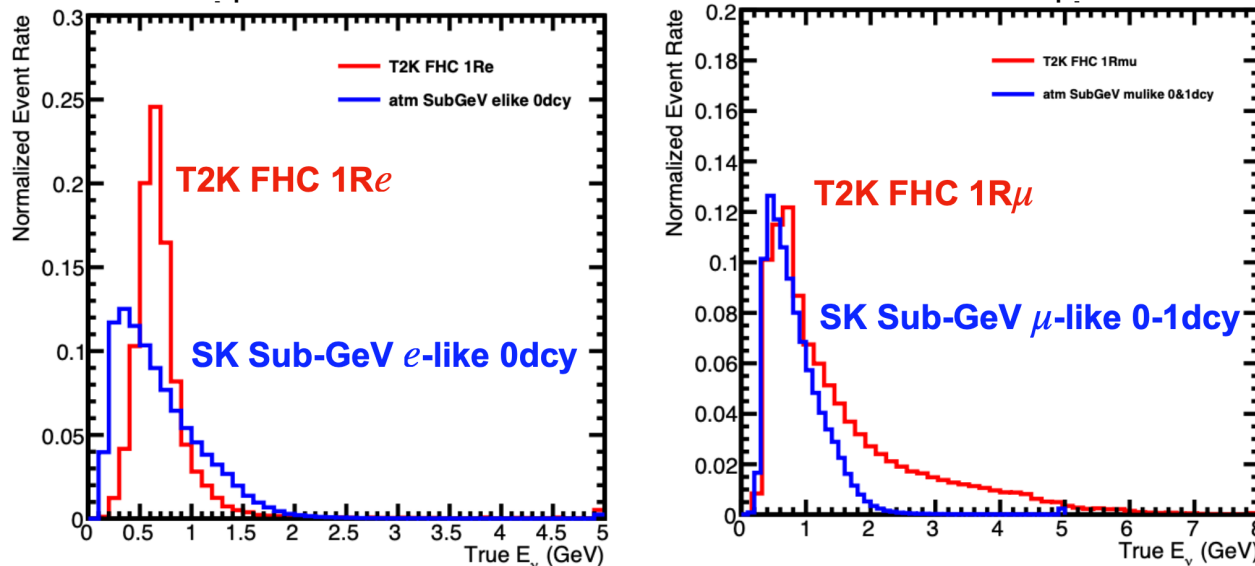
Atmospheric neutrino oscillation probability (normal ordering)

from [C. Bronner @ PANE 2018](#)



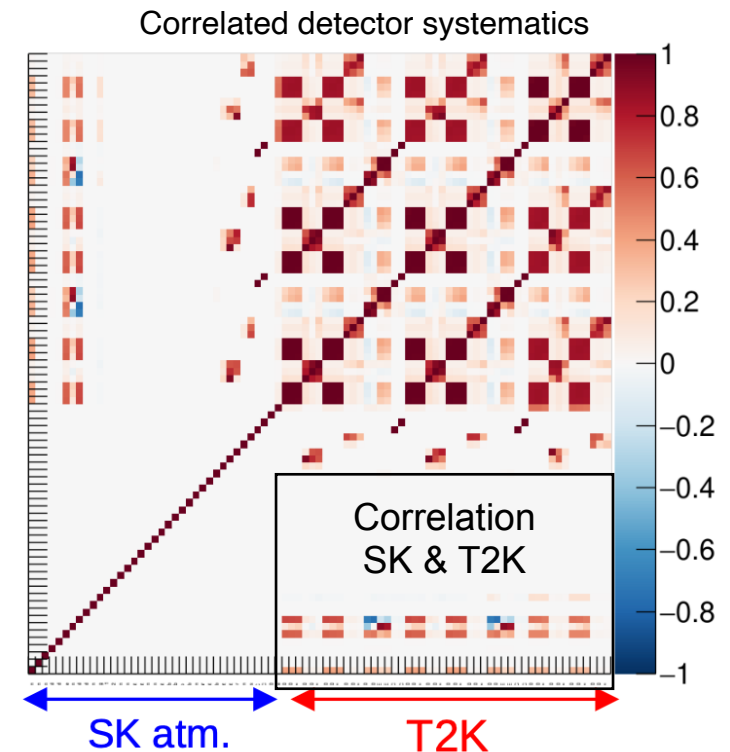
- ▶ Combining these two experiments → expect to get better sensitivity to oscillation parameters and mass ordering with increased statistics.
 - ▶ SK helps to break the **degeneracy between δ_{CP} and mass ordering** in T2K.
 - ▶ T2K can constrain $\sin^2 \theta_{23}$ better → improve the mass ordering 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

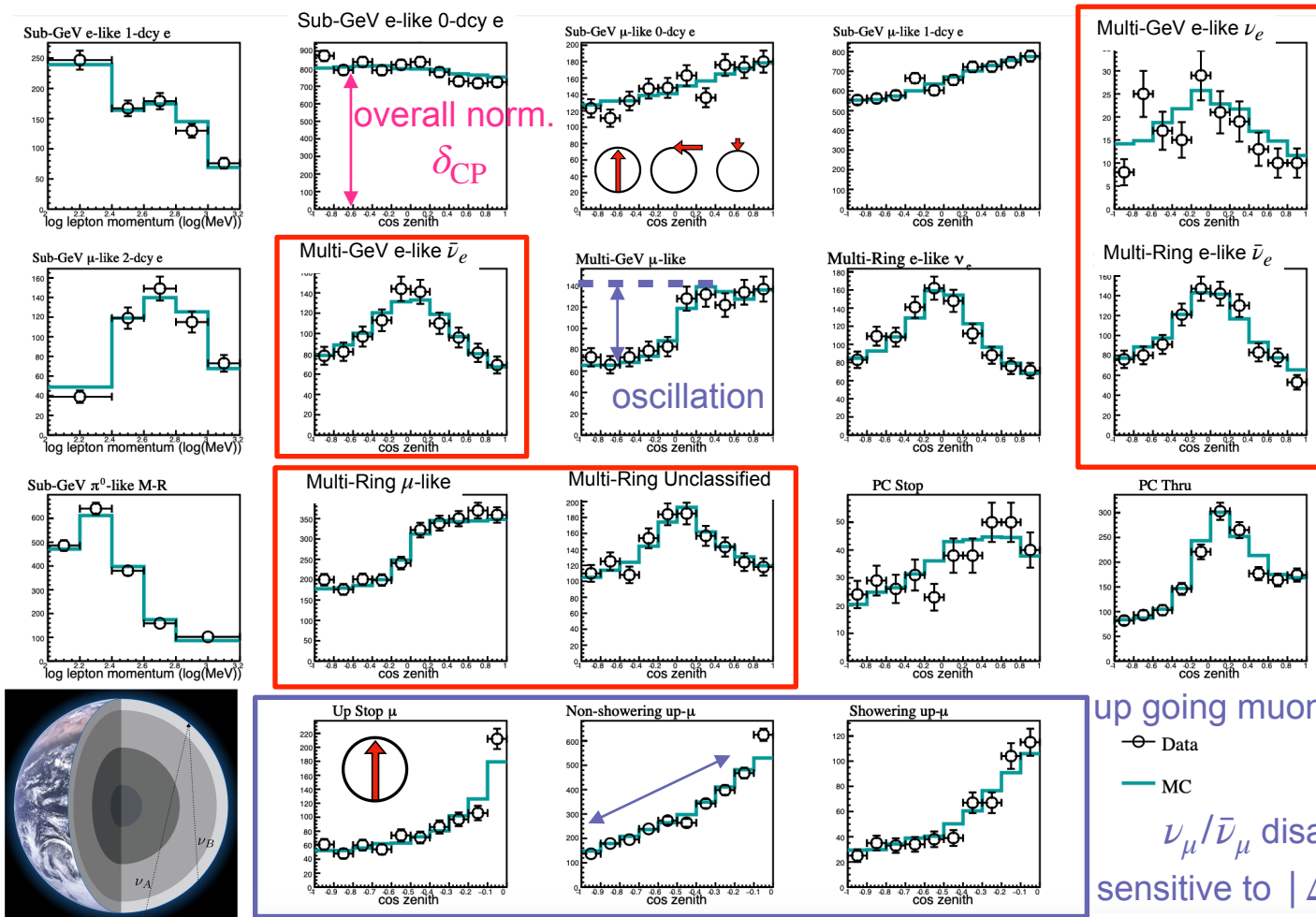


- ▶ Develop unified interaction model for T2K beam and SK low-energy samples.
 - ▶ High energy: modified SK model including additional systematics uncertainties
- ▶ The same detector/simulation software/reconstruction tool is used for the samples of both experiments.
 - ▶ Correlations of detector systematics 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 add ν_e/ν_μ ratio unc. (CRPA)	high- Q^2 params w/o ND
2p2h	T2K model w/ND280	SK model (100% error) + T2K-style shape
Resonant	T2K model w/ND280 + new pion momentum dial + NC1 π^0 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	



- ▶ 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

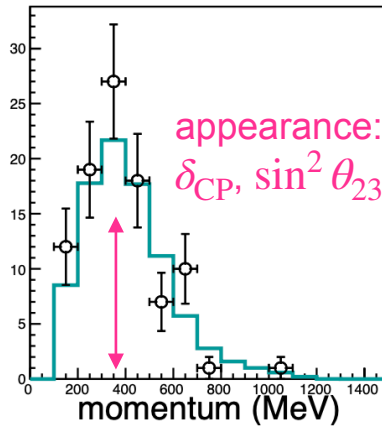
up going muons

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

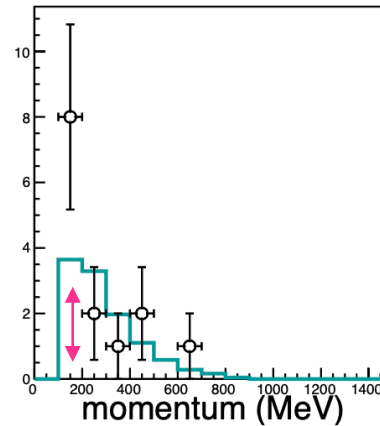
- 5 T2K beam samples with $19.7(16.3) \times 10^{20}$ POT in (anti-)neutrino mode
- Described in [[Eur.Phys.J.C 83 \(2023\) 9, 782](#)]

FHC:
 ν mode

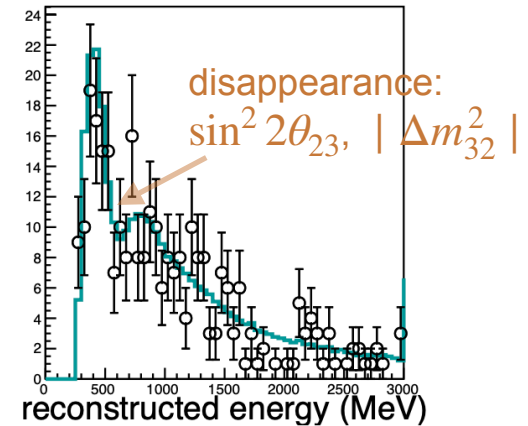
FHC 1R e-like 0 d.e.



FHC 1R e-like 1 d.e.

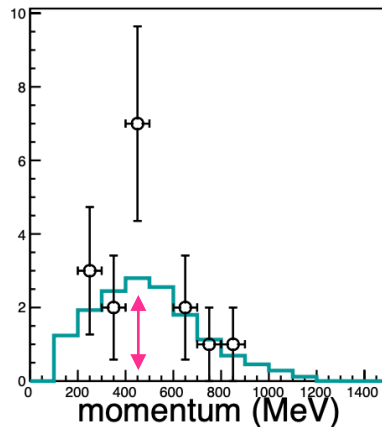


FHC 1R μ -like

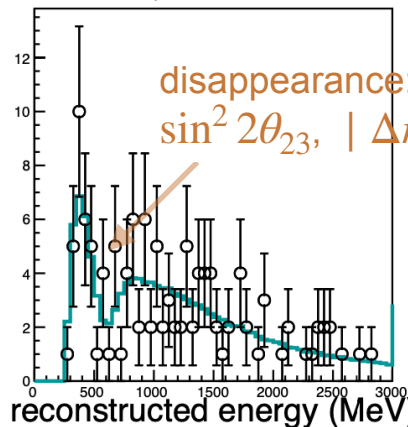


RHC:
 $\bar{\nu}$ mode

RHC 1R e-like 0 d.e.



RHC 1R μ -like



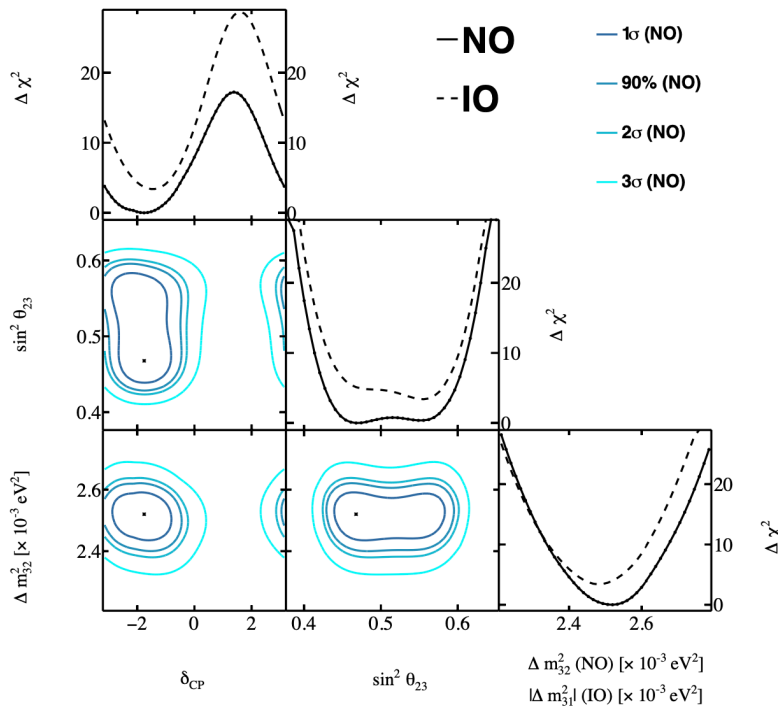
—○— Data

— MC

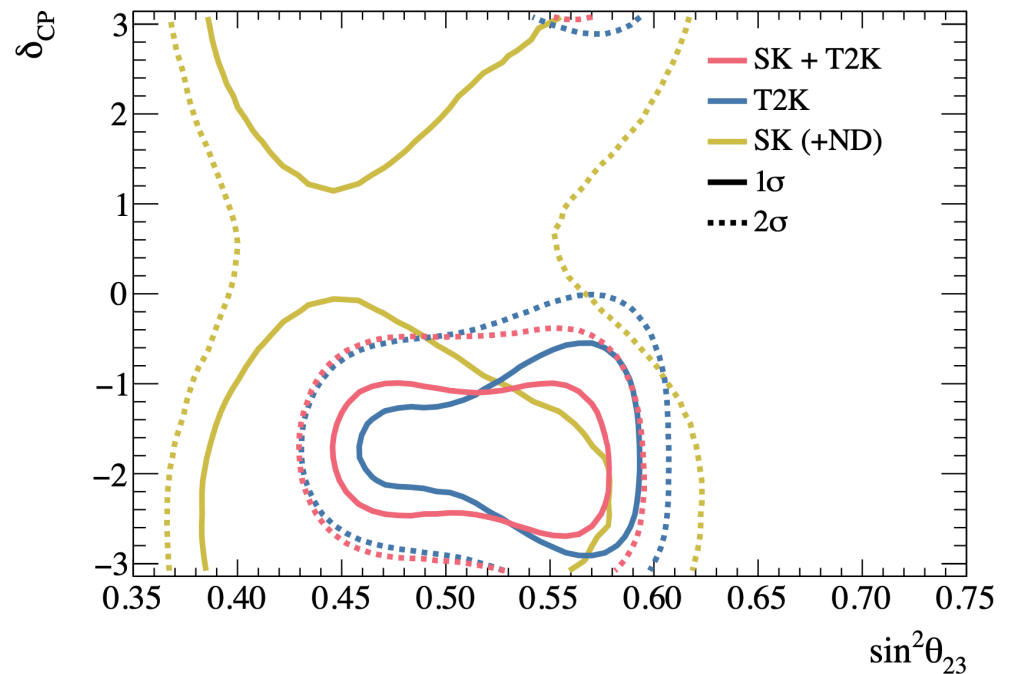
Good consistency between the atmospheric and beam samples ($p=0.24$ in Frequentist test).

- **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](#)).

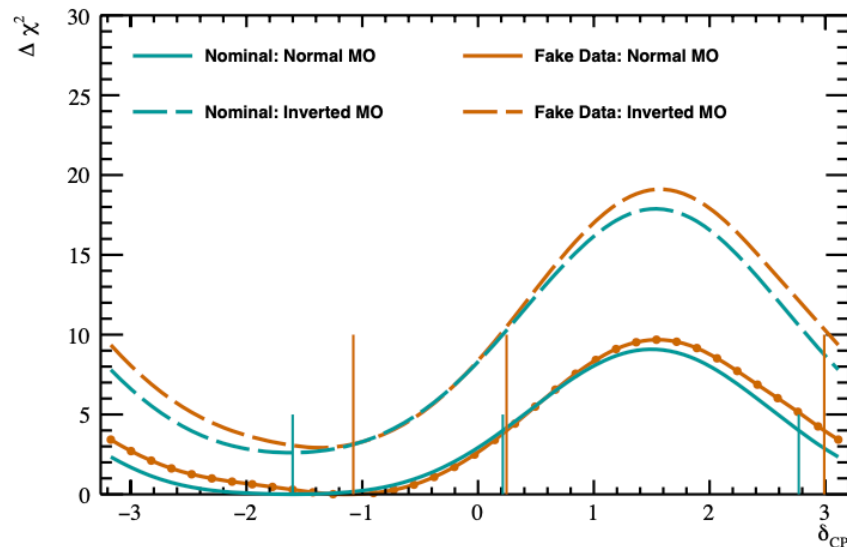
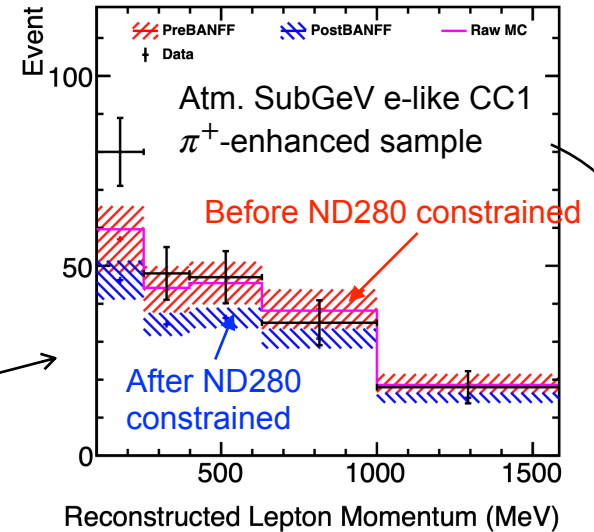
$\Delta\chi^2$ distributions of SK+T2K **frequentist** analysis



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

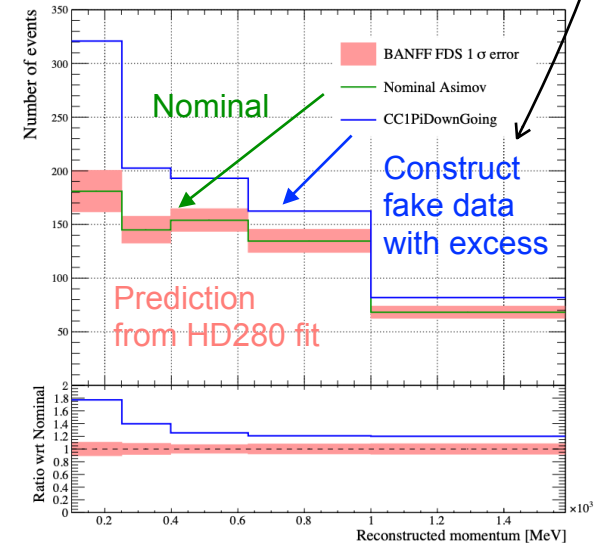


- ▶ Estimate potential biases from some possible weaknesses of our model.
- ▶ Test 14 alternative models and data-driven effects in simulated data to estimate biases.
 - ▶ Δm_{32}^2 is smeared by convolving with gaussian representing the biases.
- ▶ Example: Excess observed in down-going atmospheric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

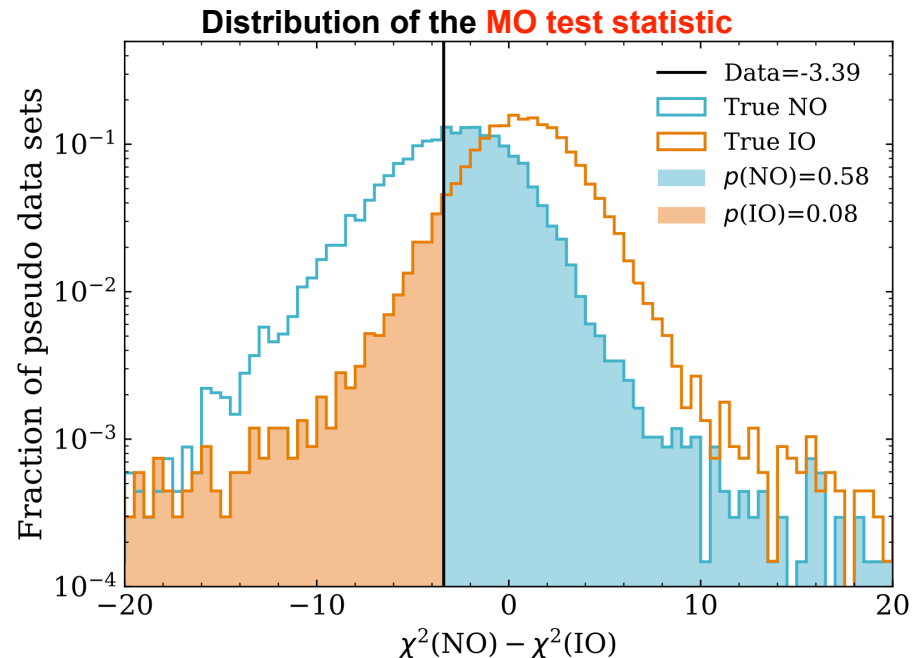
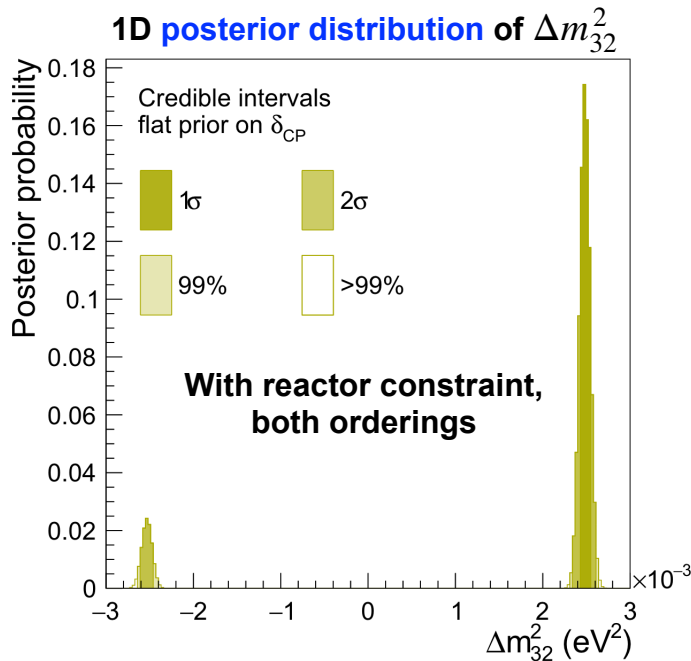


Evaluate the effect using difference between nominal fit and simulated data fit results.

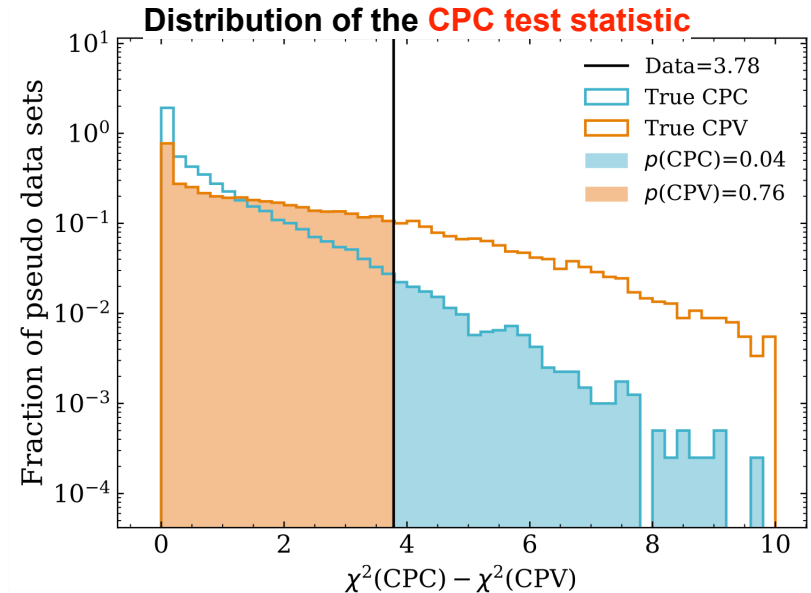
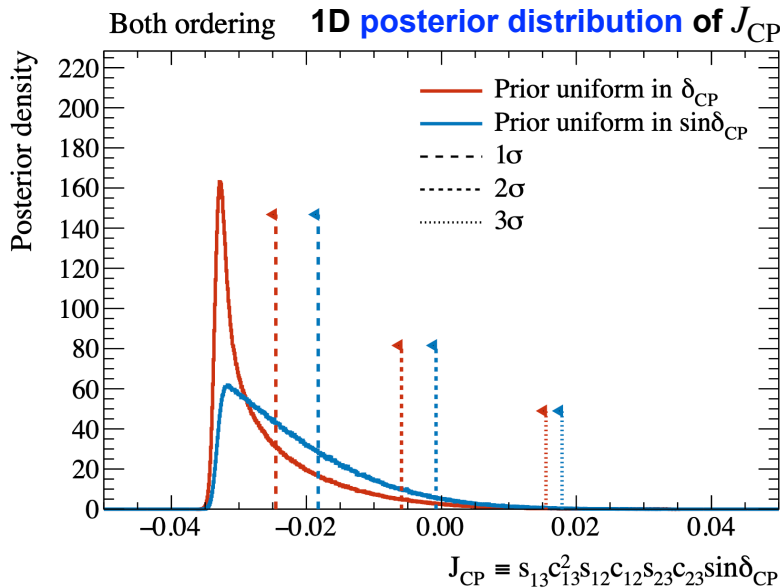
Apply the difference to data results → effect on intervals & p-values.



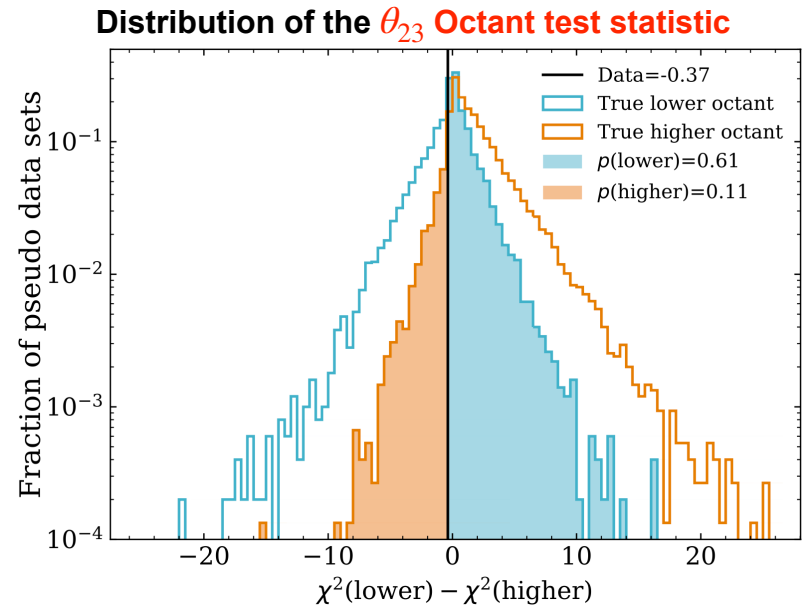
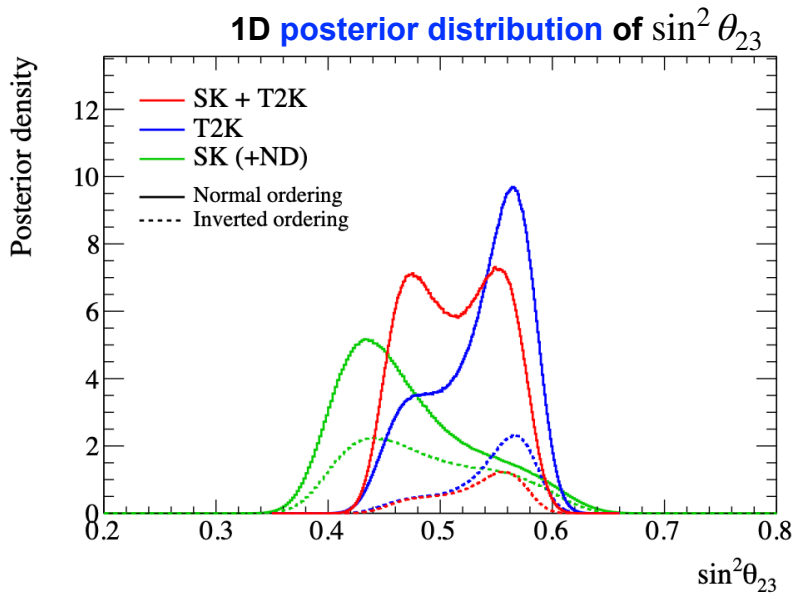
- **Bayesian**: mass ordering posterior probability for NO is ~ 0.9 , corresponds to the probability of obtaining a $\sim 1.64\sigma$ deviation assuming IO in a Gaussian assuming equal prior probabilities.
- **Frequentist**: with ensembles of constructed pseudo-experiments, weak rejection of IO with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



- **Bayesian:** The exclusion of the CP conserving values of Jarlskog invariant $J_{CP} = 0$ is 2.2σ (1.9σ) for flat δ_{CP} ($\sin \delta_{CP}$) prior.
- **Frequentist:** p-value of CP-conservation ($\sin \delta_{CP} = 0$) is about 0.04 (2σ exclusion), but increases to 0.05 after considering possible bias from CC1 π down-going excess.
- Good agreement ($p=0.75$) with an alternative hypothesis “Posterior δ_{CP} ”.
- Conclusion: slightly $< 2\sigma$ exclusion of CP conservation.



- 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 $\rightarrow \sim 0.9\sigma$ 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.



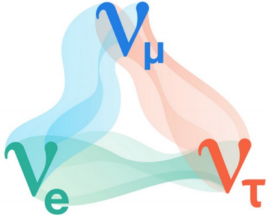
- ▶ **First** joint oscillation analysis of SK atmospheric + T2K accelerator neutrino has been performed.
- ▶ Both Bayesian and frequentist analyses are performed with additional robustness studies.
 - ▶ A limited **rejection of IO** at **90% C.L.**
 - ▶ **CPC rejected** at **slightly below 2σ** .
 - ▶ 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



Back up

- Flavor of neutrino (ν_e, ν_μ, ν_τ) changes periodically as it propagates.
- Described by mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$), mass squared differences ($\Delta M_{32}^2, \Delta M_{21}^2$), and CP phase δ_{CP} .



Flavor Eigenstates

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

PMNS Matrix

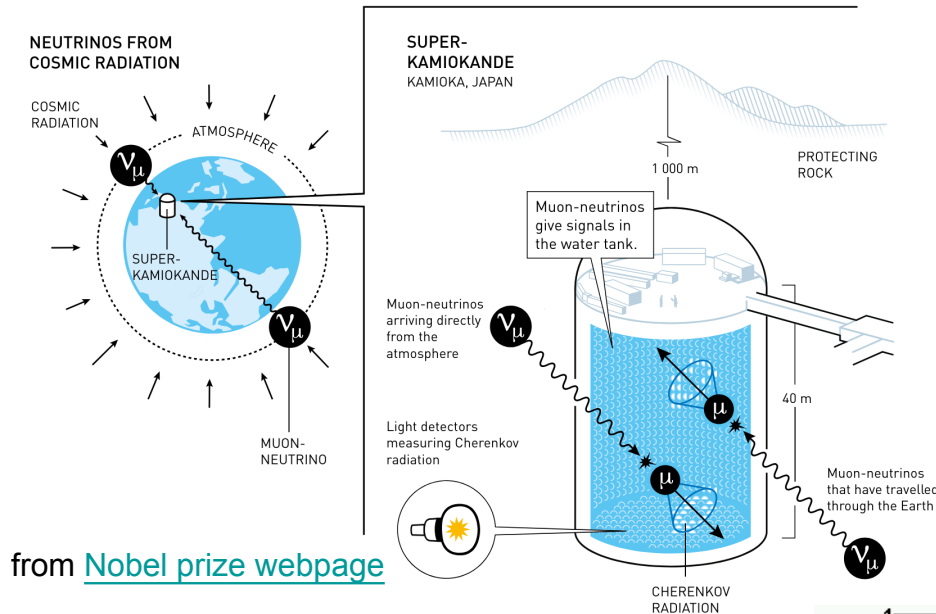


Mass Eigenstates

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

Measurement: $\theta_{12} \sim 34^\circ$ $\theta_{13} \sim 8.5^\circ$ $\theta_{23} \sim 45^\circ$

Precision: $\sin^2 \theta_{12} \sim 4\%$ $\sin^2 \theta_{13} \sim 3\%$ $\sin^2 \theta_{23} \sim 5\%$



from [Nobel prize webpage](http://nobelprize.org)

- 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 $\delta_{CP} \sim 220 - 240^\circ$, and less for $\delta_{CP} \sim 40 - 45^\circ$

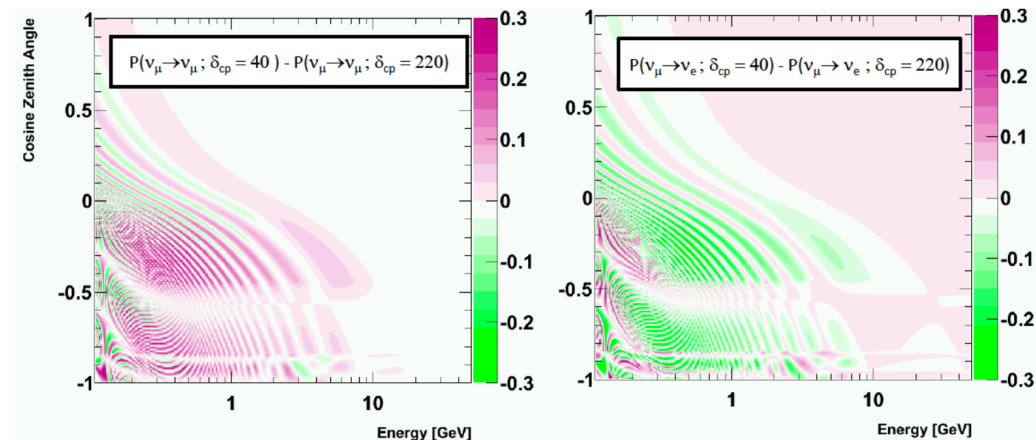
$$P(\nu_e \rightarrow \nu_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{1.27 \Delta m_{31}^2 L}{E} \right)$$

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

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

Matter effect: $\Delta m_{31,M}^2 = \Delta m_{31}^2 \sqrt{\sin^2 2\theta_{13} + (aE/\Delta m_{31}^2 - \cos 2\theta_{13})^2}$

$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (aE/\Delta m_{31}^2 - \cos 2\theta_{13})^2}$$



from [C. Bronner @ PANE 2018](#)

► The goal of Long Baseline neutrino experiments:

✓ Remaining problems: CP symmetry, Mass ordering, Octant of θ_{23}

✓ Precise measurements of θ_{23} , $|\Delta m_{31}^2|$ ($\sim |\Delta m_{32}^2|$)

◆ **Muon neutrino disappearance ($\nu_\mu \rightarrow \nu_\mu$) :**

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

Sensitive to:

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

◆ **Electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$) :**

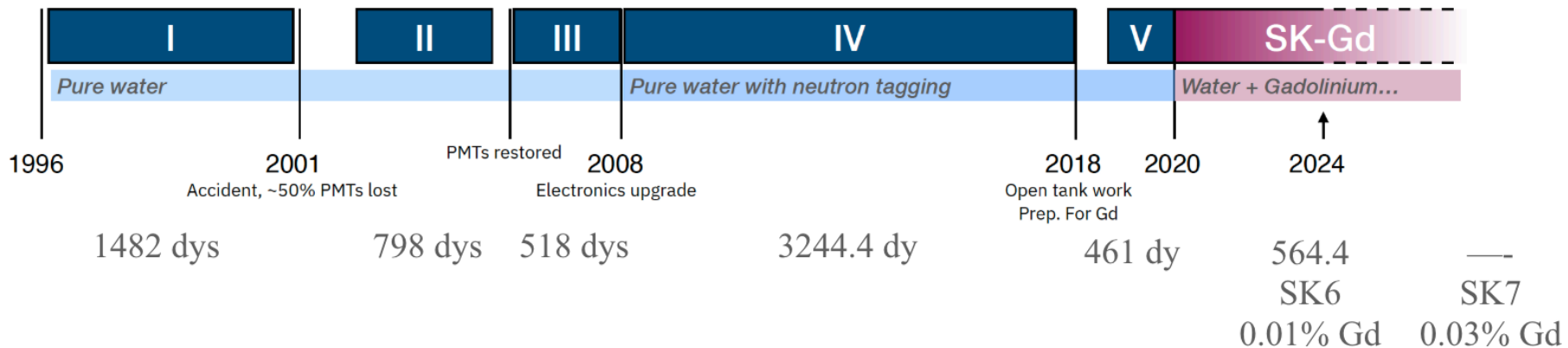
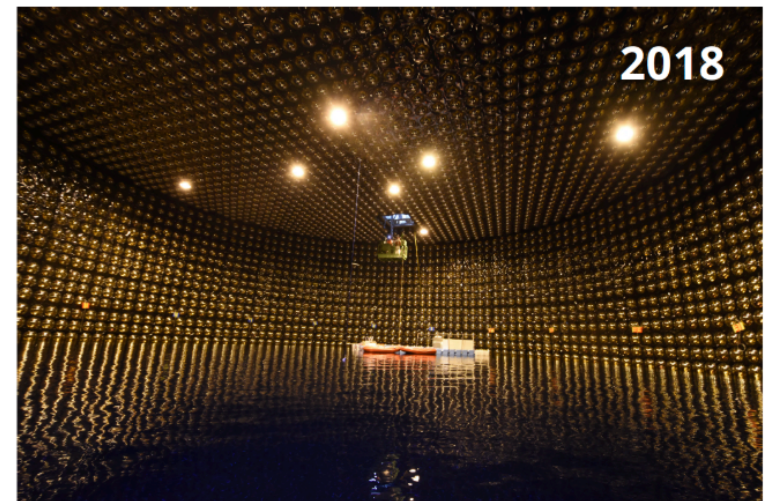
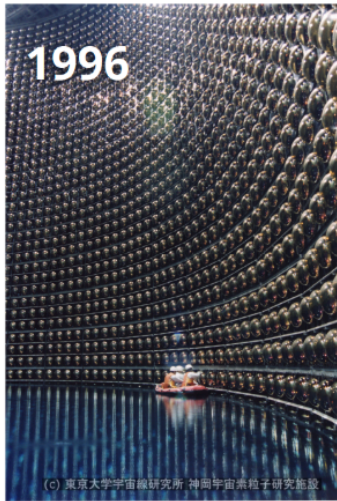
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E_\nu} \right) \left(1 + \frac{2a}{\Delta m_{31}^2} (1 - 2 \sin^2 \theta_{13}) \right) \\ - \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E_\nu} \right) \sin \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

Sensitive to:

θ_{13} , δ_{CP} , θ_{23} , and

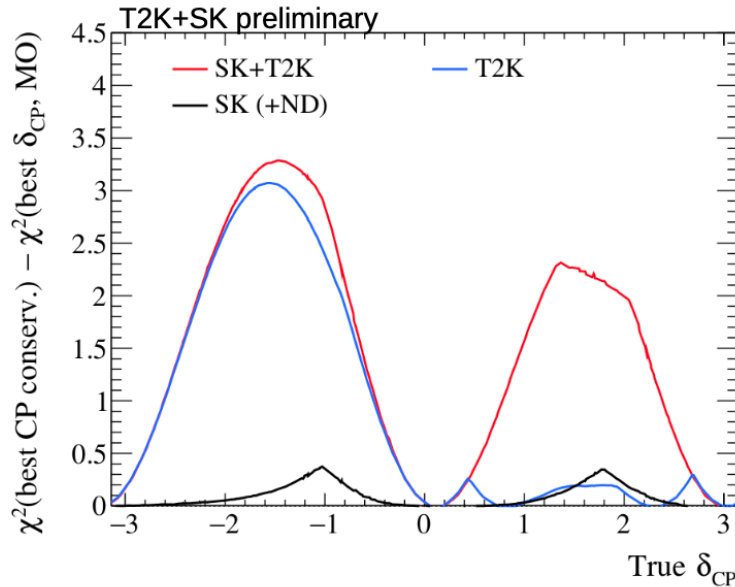
Mass ordering Δm_{31}^2

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

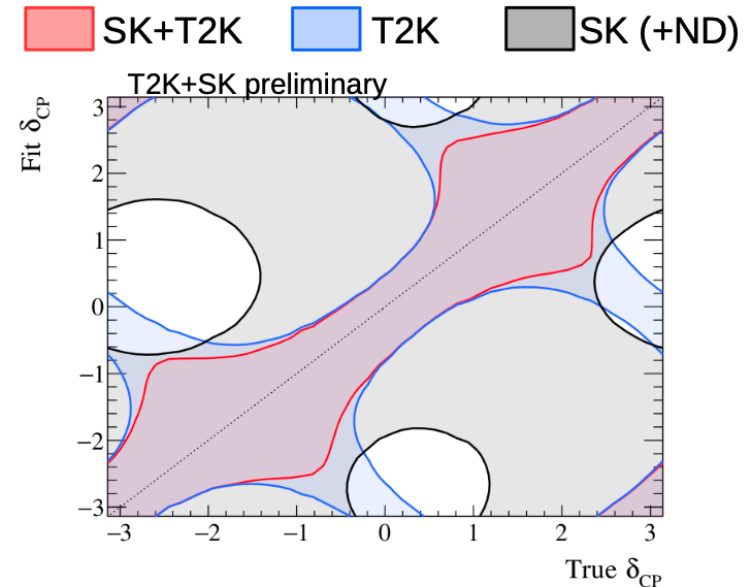


- › Sensitivity to δ_{CP} dominated by T2K
- › Joint fit allows to break degeneracy with $\cos(\delta_{CP})$ and mass ordering

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



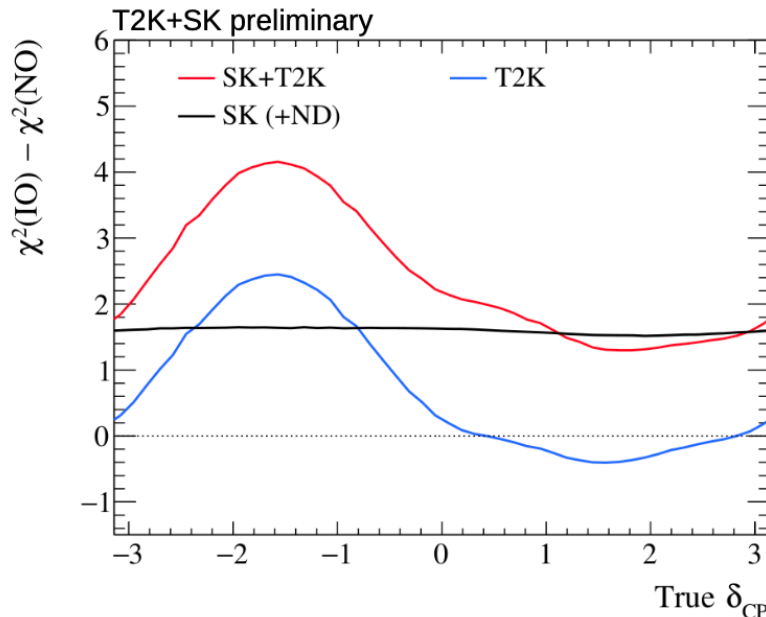
“SK (+ND)”: T2K ND constraint on interaction uncertainties used for low E atmospheric samples

True values assumed: $\sin^2(\theta_{23})=0.528$, $\Delta m^2_{32}=2.509 \times 10^{-3} \text{ eV}^2/\text{c}^4$, $\sin^2(\theta_{13})=0.0218$, NO

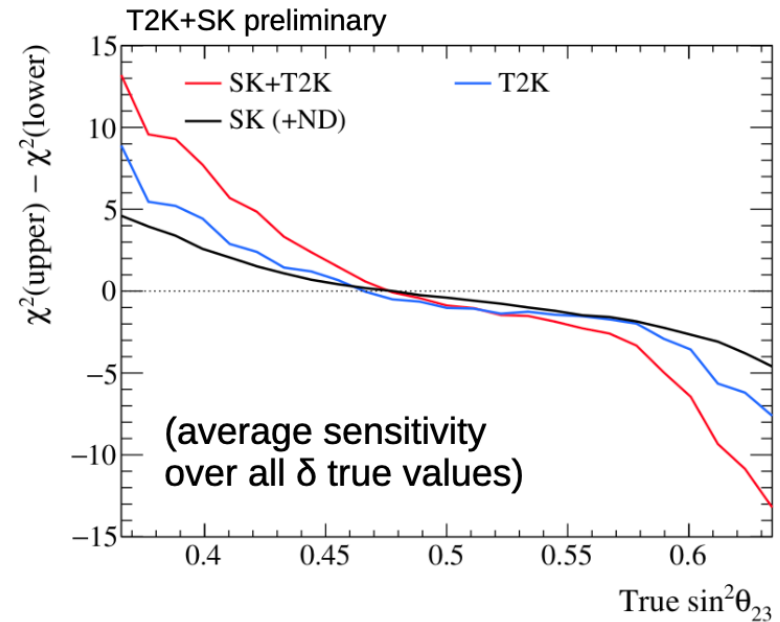
from [C. Bronner @ Neutrino 2022](#)

- 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



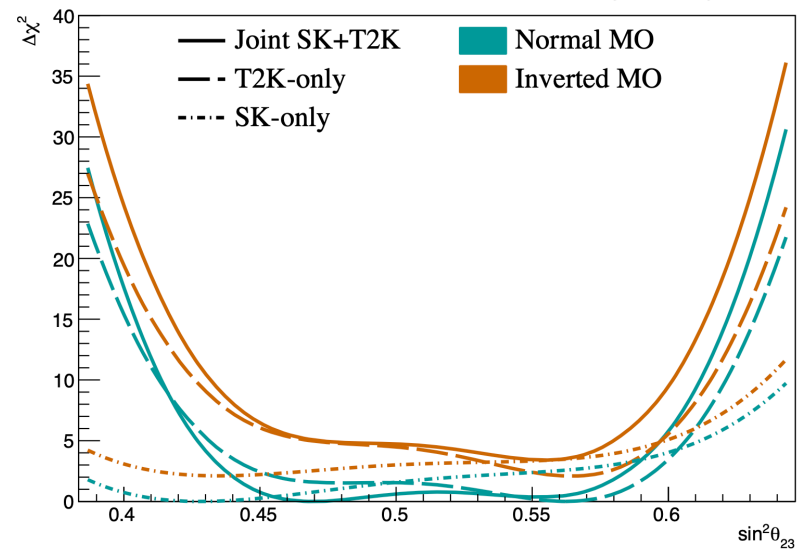
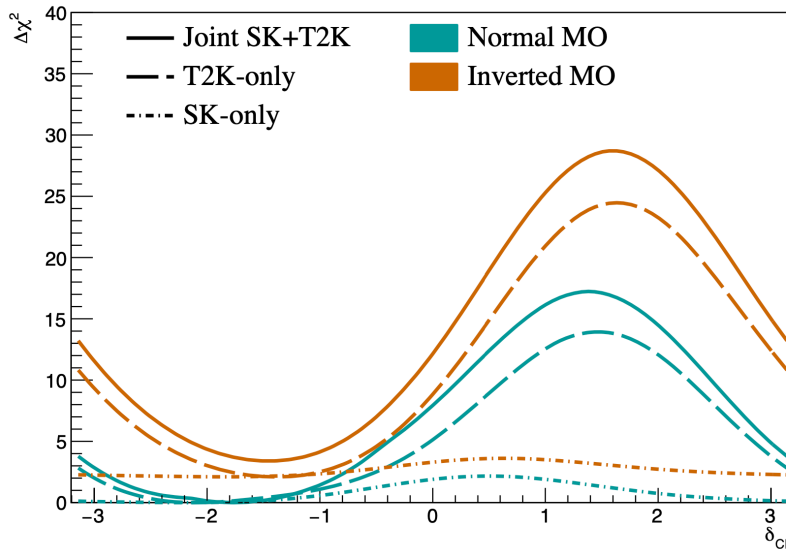
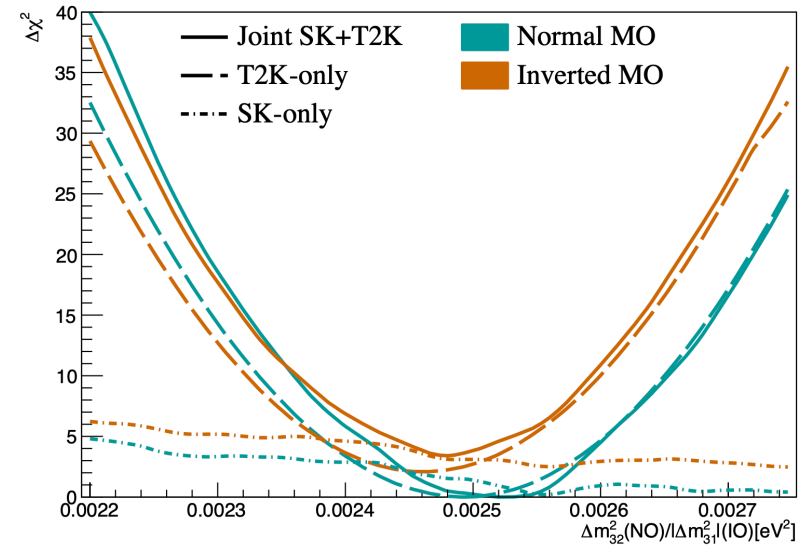
Ability to reject wrong θ_{23} octant



“SK (+ND)”: T2K ND constraint on interaction uncertainties used for low E atmospheric samples
 True values assumed: $\sin^2(\theta_{23})=0.528$, $\Delta m_{32}^2=2.509 \times 10^{-3} \text{ eV}^2/\text{c}^4$, $\sin^2(\theta_{13})=0.0218$, NO

from [C. Bronner @ Neutrino 2022](#)

- **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.



- 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)

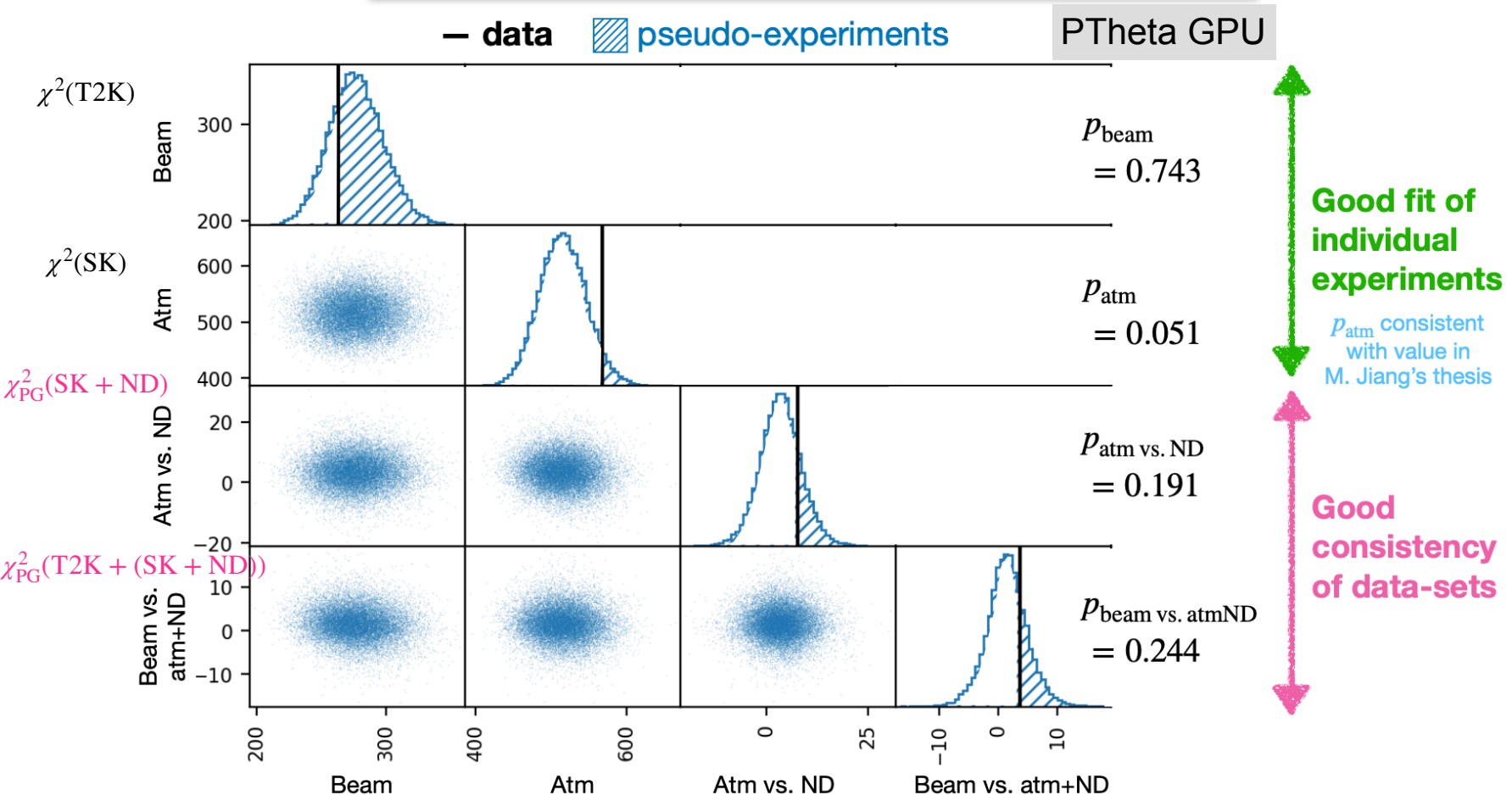
- LFG+RPA [\[ref\]](#)
- HF+CRPA [\[ref\]](#)

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	CC1 π
CC0 π non-QE alteration	CC0 π
Removal energy	Nuclear Model
Axial form factors	CCQE
Pion SI bug fix	CC1 π , CCn π
LFG	Nuclear model
CRPA	Nuclear model
Pion multiplicity	CCn π
Energy-dependent $\sigma_{\nu_e}/\sigma_{\nu_\mu}$	$\sigma_{\nu_e}/\sigma_{\nu_\mu}$
Xsec-only fit	Fit
Atmospheric down-going CC1 π	CC1 π
Atmospheric full-zenith CC1 π	CC1 π
No-migration energy scale fit	Fit

Goodness of Fit



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

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