PROCEEDINGS OF SCIENCE

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

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The nature of the neutrino mass ordering and whether neutrino oscillations violate CP symmetry remain among several open questions surrounding PMNS mixing. At present no single experiment has the ability to resolve these issues. Atmospheric neutrino data at Super-Kamiokande (SK) and accelerator neutrino data from T2K, however, offer complementary sensitivity to these puzzles. As both neutrino sources are observed at the same detector, SK, there is a clear benefit to analyzing the data sets together. Here the first such combined analysis is performed, which utilizes unified uncertainty models of both neutrino interactions and the detector response. Combined constraints on open questions in the PMNS paradigm are presented, using 3244.4 days of SK atmospheric neutrino data and beam neutrino data corresponding to 3.6×10^{21} protons-on-target from T2K's first 10 run periods. The analysis provides a marginal rejection of CP conservation and the inverted mass ordering hypotheses, with significance levels of 1.9σ and 1.2σ respectively.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

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1. Introduction

Neutrino oscillation refers to the phenomenon where a neutrino produced with a definite flavor can transform into a neutrino of a different flavor as it travels. It is found that this is because the neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) are quantum superpositions of the mass eigenstates (ν_1, ν_2, ν_3). The relationship between the neutrino flavor eigenstates and the mass eigenstates is described by the PMNS matrix, which can be parameterized in terms of three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and one CP-violating phase (δ_{CP}). The neutrino oscillation experiments also provide information about two main mass-squared differences: $\Delta m^2_{ij} = m^2_i - m^2_j$ where m_i and m_j are the masses of the i^{th} and j^{th} neutrino mass eigenstates. Over several decades, many neutrino experiments have made precise measurements on many of these parameters, but there are still several unresolved puzzles, such as determining the mass ordering (MO), understanding CP violation, and resolving the octant of θ_{23}.

The Super-Kamiokande (SK) experiment and Tokai-to-Kamioka (T2K) experiment are neutrino oscillation experiments to solve these remaining puzzles. The SK detector [1] is a large water Cherenkov detector located in the Kamioka mine in Gifu, Japan. It measures atmospheric neutrinos which are produced by the interaction of cosmic rays with nuclei in the Earth's atmosphere. The neutrino has a wide ranges of energies (MeV~TeV) and propagation baselines (15~13000 km). The T2K experiment [2] measures neutrino oscillations using a primary $\overset{(-)}{\nu}_\mu$ beam produced at the J-PARC, located in Ibaraki, Japan. A set of near detectors (mainly ND280 and INGRID), which are located 280 meters down the beamline, are used to constrain cross-section and flux models. SK detector is located 2.5° off of the beam axis and used as a far detector to measure neutrinos after oscillation over a baseline of 295 km.

2. Motivation of joint analysis

As neutrinos pass through the matter in the Earth, there would be a modification of neutrino oscillation behavior as opposed to traveling in a vacuum. This so-called matter effect will cause a resonance region in the neutrino oscillation probability [3]. This resonance enhancement will only appear for neutrinos in the normal mass ordering while it will only appear for antineutrino in the inverted mass ordering. In addition, the size of the resonance depends on the neutrino mixing angles of $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$. By measuring the oscillation probabilities of atmospheric neutrinos and antineutrinos, especially those passing through the Earth at different angles, SK can probe the MO and the octant of θ_{23}. In T2K, a precise measurement of oscillation parameters can be achieved through disappearance ($\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$) and appearance ($\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$) channels, with the almost pure $\overset{(-)}{\nu}_\mu$ flux peaked at 600 MeV and a known direction for SK [4]. $\left|\Delta m^2_{32}\right|$ and $\sin^2\theta_{23}$ can be determined by the peak energy and the amplitude of the disappearance probability. The MO and the value of $\sin\delta_{\mathrm{CP}}$ both affect the appearance probability of neutrino and antineutrino asymmetrically. $\sin\delta_{\mathrm{CP}}$ has a large area of degenerate phase space with MO due to limited matter effect and similarity of the effects on oscillation from both parameters.

By combining SK and T2K experiments together, it is expected to get better sensitivity to oscillation parameters and MO with increased statistics. In addition, SK helps to break the degeneracy between $\sin\delta_{\mathrm{CP}}$ and MO in T2K. With more precise measurement of $\sin^2\theta_{23}$ in T2K, it is expected to improve the MO sensitivity in SK. Additionally, T2K and SK share samples with similar energy ranges. The T2K near detector can be leveraged to constrain cross-section uncertainties in low-energy atmospheric neutrino samples, thereby enhancing the sensitivity of the SK analysis.

3. Analysis methods

The analysis is based on the previous analyses from both collaborations [4, 5]. To do the joint analysis, a unified interaction model is developed for T2K beam and SK low-energy samples. It is based on T2K model with constraints from near detector. Some extra parameters are added to cover important uncertainties for the atmospheric analysis. For high energy ranges, a modified SK model including additional systematic uncertainties is used. As for the detector model, the same detector simulation software and reconstruction tool are used for the samples of both experiments. Correlations between detector systematics are investigated by varying the detector parameters of the SK model and evaluating the effects on the number of events in the different samples of the two experiments. These correlation will be included in the fitter for the combined analysis.

The analysis is conducted using both Bayesian and frequentist methods. In the Bayesian framework, the marginal likelihoods for the parameters of interest are evaluated through the Markov Chain Monte Carlo (MCMC) method. In contrast, the frequentist approach computes the profile likelihood over a fixed grid of the oscillation parameters. Despite their different treatments of nuisance parameters, both statistical methodologies yield similar conclusive results [6].

Additional robustness studies are done to estimate potential biases from some possible weaknesses of our model. One example of the studies is about the excess observed in down-going atmospheric data aggravated by T2K near detector constraint. This motivates new systematics and modified event selection. To test this excess which may originate from our insufficient understanding of the data, we evaluate the effect using the difference between nominal fit and simulated data fit results. The difference is applied to the data results to check the effects on intervals and p-values which will be mentioned later. Fourteen tests are done and some of them show non-negligible biases in Δm^2_{32}, so we decide to smear it by convolving with Gaussian. The sigma is 3.6×10^{-5} eV^2 for Bayesian results.

4. Results on neutrino oscillation parameters

The analysis uses 18 SK atmospheric samples with 3244.4 days of data taking [5] and 5 T2K beam samples with $19.7(16.3) \times 10^{20}$ protons-on-target (POT) in (anti-)neutrino mode [4]. The credible intervals from the posterior probability distributions from Bayesian study and the $\Delta\chi^2$ distributions from frequentist study can be found in Fig. 1. A smaller $\Delta\chi^2$ is found for normal mass ordering and the maximum CP violation. The constraints are largely dominated by T2K but SK also has a significant contribution on the octant and MO [6].

For the CP-violating phase δ_{CP}, the results from both Bayesian and frequentist analyses are shown in Fig. 2. The exclusion of CP-conserving values of the Jarlskog invariant [7] ($J_{\mathrm{CP}} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{\mathrm{CP}}$) is observed at 2.2σ significance with a flat δ_{CP} prior, and 1.9σ with a flat $\sin\delta_{\mathrm{CP}}$ prior, after accounting for robustness studies. The frequentist significance of CP violation is evaluated by generating ensembles of pseudo-experiments. These

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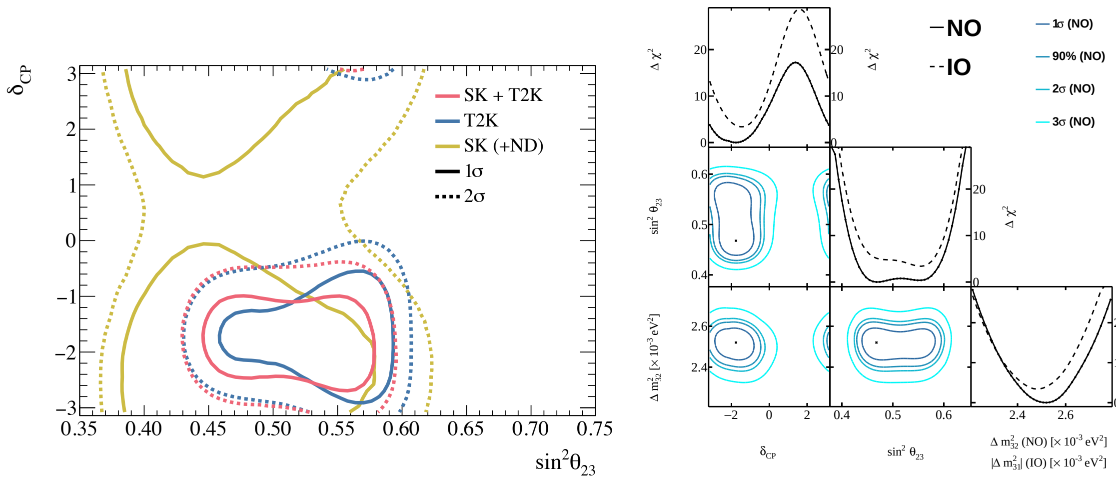

Figure 1: (Left): The 2D credible regions of ($\sin^2\theta_{23}$, δ_{CP}) obtained with the SK, T2K, and combined datasets. The MO is accounted for through marginalization, and a uniform prior is applied to δ_{CP}. The plot is from Ref. [6]. (Right): The $\Delta\chi^2$ distributions of δ_{CP}, $\sin^2\theta_{23}$ and Δm^2_{32} ($|\Delta m^2_{31}|$) from frequentist study with combined dataset.

ensembles incorporate statistical fluctuations and vary the nuisance oscillation parameters and systematic uncertainties. The nuisance oscillation parameters are randomized based on their posterior probability distributions, while the systematic uncertainties follow their prior distributions. The test statistic is based on the log-likelihood ratio comparing the CP-conserving hypothesis ($\sin\delta_{CP} = 0$, which corresponds to $J_{CP} = 0$) to the alternative without any assumptions. The p-value for the CP-conservation hypothesis is approximately 0.04, corresponding to an exclusion at the 2σ level. This increases slightly to 0.05 when potential biases, such as the observed CC1π^+ down-going event excess, are considered. The data shows good agreement with an alternative hypothesis based on posterior δ_{CP}, with a p-value of 0.75. In conclusion, the data provide a marginal exclusion of CP conservation, slightly below the 2σ level.

For the MO, the results from both Bayesian and frequentist analyses are displayed in Fig. 3. The posterior probability for the normal ordering is approximately 0.9, which corresponds to a 1.64σ deviation assuming the inverted ordering in a Gaussian framework, under the assumption of equal prior probabilities. Based on ensembles of constructed pseudo-experiments similar to the test for CP violation, the inverted ordering is weakly rejected with a p-value of 0.08, corresponding to a confidence level (CL_s) of 0.18 [6]. Robustness tests indicate that potential biases are minimal, with a change in the p-value of just 0.001. Therefore, we can conclude that the analysis shows a weak preference for normal ordering, with a confidence level of approximately 90%.

For the octant of θ_{23}, results from both Bayesian and frequentist analyses are shown in Fig. 4. Different preferences for the octant emerge between experiments: SK data show a preference for the lower octant, while T2K data favor the higher octant. In the combined analysis, the Bayesian posterior probability indicates a preference for the upper octant, while the $\Delta\chi^2$ from the best-fit value slightly favors the lower octant. In the Bayesian analysis, the posterior probability for the upper octant is 0.64, corresponding to approximately a 0.9σ deviation from the lower octant. On

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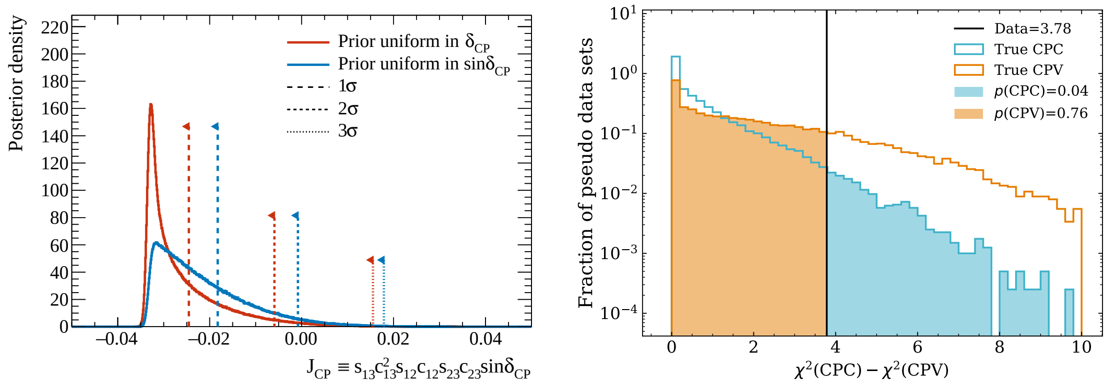

Figure 2: (Left): The posterior density distribution for the Jarlskog invariant with 1, 2, 3σ credible intervals. In the plot both MOs are marginalized over and a uniform prior in either δ_{CP} or $\sin\delta_{CP}$ is assumed with combined dataset. The plot is from Ref. [6]. (Right): Distribution of the CP-conserving (CPC) and CP-violating (CPV) test statistics under the true CPC and CPV hypotheses with combined dataset.

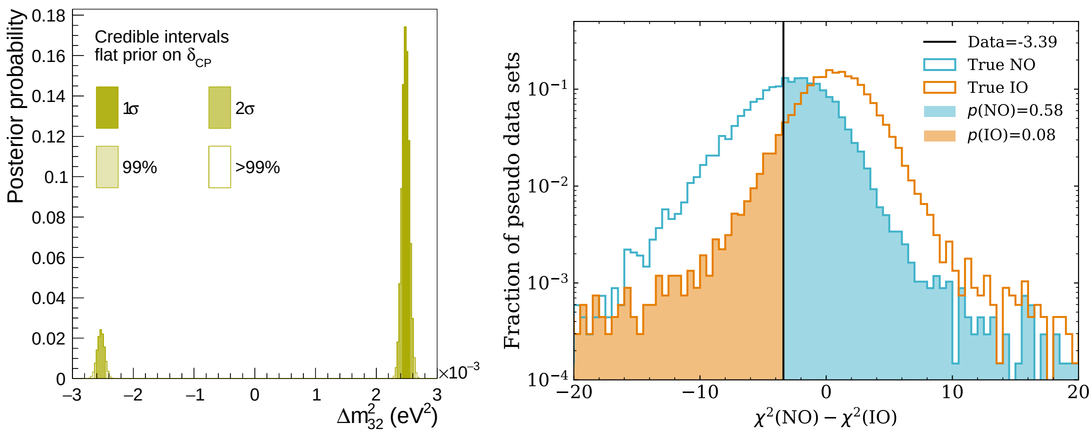

Figure 3: (Left): The posterior density of Δm^2_{32} obtained with the combined dataset. The plus (minus) values correspond to normal (inverted) mass ordering. (Right): Distribution of the test statistic distribution for the mass ordering, comparing the true normal and inverted ordering hypotheses, based on the combined dataset. The plot is from Ref. [6].

the other hand, the frequentist analysis shows that $\chi^2(\text{lower} - \text{higher})$ is only -0.37, and the p-value (or CL_s) for the higher θ_{23} octant is 0.11 (confidence level of 0.28). In conclusion, there is no strong or obvious preference for either octant based on the current data.

5. Conclusions and perspectives

A joint analysis of SK atmospheric and T2K accelerator neutrino data within a unified framework for Bayesian and frequentist statistical inferences is successfully carried out. With additional robustness studies, the results show a limited rejection of inverted mass ordering at 90% C.L. and a slightly below 2σ rejection of CP conservation. In the future, there is a potential for more sensitive combined analyses between SK and T2K, including more than 100% increases of the SK

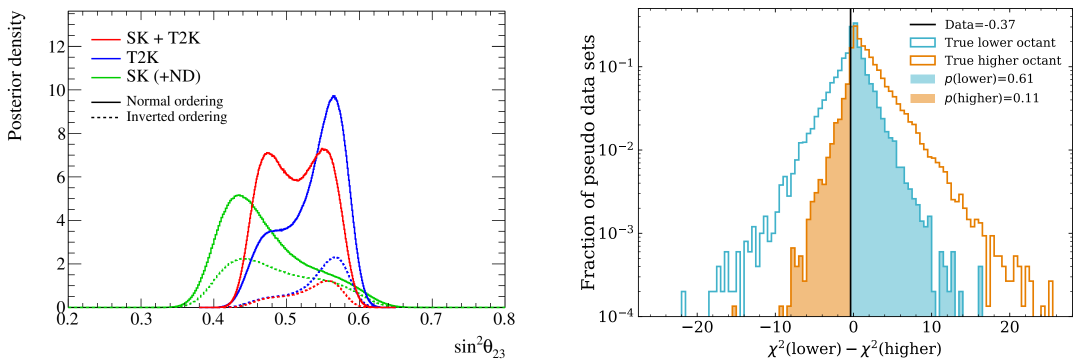

Figure 4: (Left): The posterior density of $\sin^2\theta_{23}$ obtained with the SK, T2K, and combined datasets. (Right): Distribution of the octant test statistic under true lower and higher octant hypotheses with combined dataset.

statistics [3] and 9% POT increase on FHC mode in T2K if using their up-to-date dataset. This is an important step towards the combined beam and atmospheric data analyses planned by next generation neutrino oscillation experiments such as HyperK.

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