PROCEEDINGS OF SCIENCE

T2KSK Joint ν Oscillation Sensitivity

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The sensitivity of a joint oscillation analysis between the Tokai-to-Kamioka (T2K) accelerator and Super-Kamiokande (SK) atmospheric neutrinos is presented. The two experiments have been playing leading roles in the global constraints on neutrino oscillation parameters such as δ_{CP}, θ_{23}, and neutrino mass ordering (MO). The atmospheric neutrinos observed in SK have a good sensitivity to the MO, meanwhile a precise measurement of the leptonic CP violation phase (δ_{CP}) can be achieved by the exclusive $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation measurements in accelerator neutrinos. However, possible degeneracy limits the measurement precision in each experiment. In this work, we perform a joint fit to overcome this obscurity with the correlation of systematic uncertainties taken into account. The impact of T2K near detector constraints on the fit of SK atmospheric neutrinos is tested, and an increase of sensitivity to δ_{CP} and MO is demonstrated.

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1. Introduction

The PMNS matrix [1] is well-established for the three-flavor mixing of active neutrinos' mass and weak flavor eigenstates, which depends on four free parameters under the assumption of Dirac particle that is considered in this work — three mixing angles θ_{ij}'s for $i \neq j$, $i, j = 1, 2, 3$ and δ_{CP}. Besides the free parameters in the PMNS matrix, the neutrino oscillation probability also depends on the differences of squares of neutrino mass eigenvalues $\Delta m^2_{ij} \equiv m^2_i - m^2_j$, the length of oscillation baseline L, and the neutrino energy E_ν. Over the past decades strong constraints on θ_{12}, θ_{13}, Δm_{21}, and $|\Delta m^2_{32}|$ (or $|\Delta m^2_{13}|$) have been achieved by various experiments [1], while relatively large uncertainties still exist in θ_{23}, δ_{CP}, and MO. By convention, it is referred as normal ordering (NO) if $m_1 < m_2 < m_3$ and inverted ordering (IO) if $m_3 < m_1 < m_2$.

2. T2K and SK

T2K is a long-baseline neutrino oscillation experiment where a $\nu_\mu(\bar{\nu}_\mu)$ beam produced at the Japan Proton Accelerator Complex (JPARC) in Ibaraki, Japan travels 295 km towards SK — a 50 kt cylindrical water Cherenkov detector located in Gifu, Japan that is 2.5° off-axis from the T2K neutrino beam center. The off-axis arrangement helps achieve a narrow energy spectrum of $E_\nu \sim 600$ MeV. The selection of ν_μ and $\bar{\nu}_\mu$ is achieved by changing the polarity of B-field seen by the hadrons in the focusing magnets. At ~280 m down the beam-line from the proton target, a near detector (ND) suite houses both on and off-axis tracking detectors to measure the neutrino properties before oscillation takes place. The on-axis ND monitors the beam stability and intensity. The off-axis ND, with both carbon and water targets and sitting in the same direction as SK, produces constraints on the "un-oscillated" neutrino flux and cross section systematic uncertainty parameters. T2K measures both the $P\big(\nu_\mu(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu)\big)$ survival and the $P\big(\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)\big)$ appearance possibilities, for both neutrino and anti-neutrino beam modes. In the T2K analysis, the effect of δ_{CP} manifests itself via the difference between ν_e and $\bar{\nu}_e$ appearances that depends mostly on $\sin\delta_{CP}$. However, the yet unknown MO causes additional uncertainty on δ_{CP} due to its similar effect to the ν_e and $\bar{\nu}_e$ appearances. This degenerate effect is demonstrated in Fig. 1.

On the other hand, in SK the atmospheric neutrino oscillation is measured by the neutrino event rate's dependency on the observed lepton momentum and zenith angle. Compared to the T2K accelerator neutrinos, the SK atmospheric ones cannot provide as strong a constraint on δ_{CP} due to the difficulty of distinguishing neutrino from antineutrinos in a water Cherenkov detector for those of the similar energies to the T2K samples. However, the matter effect [2] from high-density regions inside the earth produces unique resonance signatures at $E_\nu \sim \mathcal{O}(1)$ GeV in either of the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ channels depending on the MO, and is mostly uncorrelated with δ_{CP}. Hence, a simultaneous oscillation analysis with the two neutrino sources can improve the measurements by combining the strength of each reference experiment.

3. Analysis Overview

The T2K neutrino samples considered in this work correspond to those collected throughout T2K Run 1 ~ 10 (3.6×10^{21} POT) [3]. For the atmospheric samples, the full SK-IV period (3244.4

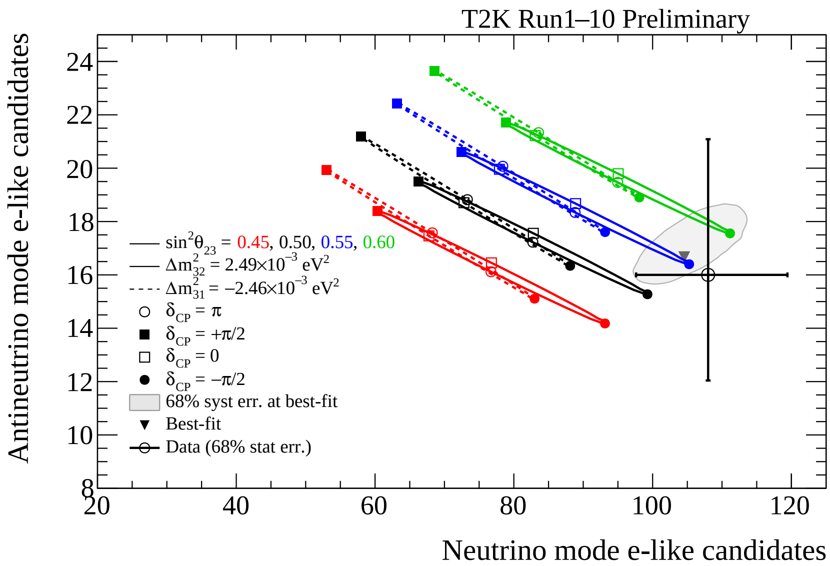


Figure 1: The effects from neutrino oscillation parameters to ν_e event rate on the x-axis and $\bar{\nu}_e$ on the y-axis, based on 3.6×10^{21} Proton-on-Target (POT). Different colors represent different true $\sin^2\theta_{23}$, marker styles represent different true $\delta_{\rm CP}$, and solid (dashed) lines true NO (IO). The latter two parameters have degenerate effects to the event rates. Data is shown with statistical error. T2K's best-fit prefers $\delta_{\rm CP} \approx \pi/2$, $\sin^2\theta_{23} > 0.5$, and NO.

days) is used [4]. Most of the T2K neutrino samples have $E_\nu < 1$ GeV, while the SK atmospheric samples have a much wider energy spectrum spanning both the "sub-GeV" and "multi-GeV" regions. Compared to the T2K samples, the atmospheric samples have a greater sample size in the "sub-GeV" region by $1 \sim 2$ orders of magnitudes.

A coherent systematic uncertainty model is newly constructed for the purpose of this joint oscillation analysis based on the models used in each experiment respectively. The beam and atmospheric flux models are implemented uncorrelated in this work due to the different approaches to constrain the uncertainties at present. Even though T2K and SK use the same detector, they have adopted different detector systematic uncertainty models. The potential correlation between the two existing detector models was verified to be negligible, and thus they are implemented without correlation in this iteration of the analysis. Given the similar energies of the neutrinos in T2K and "sub-GeV" SK atmospheric samples, a common neutrino-nucleus interaction model is implemented for these samples with the T2K ND constraints. For "multi-GeV" samples, most of the neutrino interaction model in this work is the same as in the SK atmospheric analysis, except for the charged-current quasi-elastic (CCQE) scattering that shares common parameters with the T2K and "sub-GeV" samples. In addition to the existing systematic parameters, a few more are devised for CCQE and resonant 1π interactions to ensure that the common model is suitable for both experiments' samples.

4. Joint Sensitivity

This work uses a maximum likelihood approach to produce the Bayesian and frequentist results of experimental sensitivities [5] to oscillation parameters. The assumed true values of neutrino oscillation parameters are listed in Table 1.

Δm^2_{21}	Δm^2_{32} (NO) / Δm^2_{13} (IO)	$\sin^2\theta_{23}$	$\sin^2\theta_{12}$ ($\sin^2 2\theta_{12}$)	$\sin^2\theta_{13}$ ($\sin^2 2\theta_{13}$)	δ_{CP}	MO
7.53×10^{-5} eV^2	2.509×10^{-3} eV^2	0.528	0.307 (0.851)	0.0218 (0.0853)	−1.601	Normal

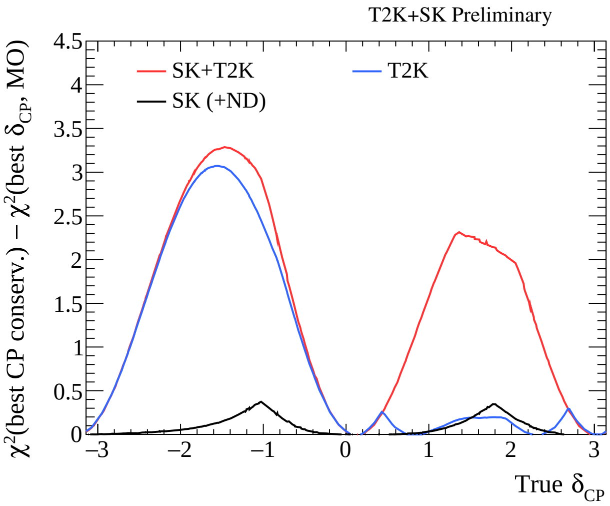
Table 1: Assumed true values of the neutrino oscillation parameters for the sensitivity estimation.

The aforementioned degeneracy between δ_{CP} and MO is reduced by this joint analysis. Fig. 2a shows the sensitivity to reject CP conservation hypotheses for the different possible true δ_{CP} values. The T2K-only analysis, subject to the δ_{CP}-MO degeneracy, can only distinguish CP violation from conservation in roughly half of the phase space. By the inclusion of SK atmospheric samples in this analysis, the sensitivity is increased especially in the region where the T2K-only analysis reaches its limits.

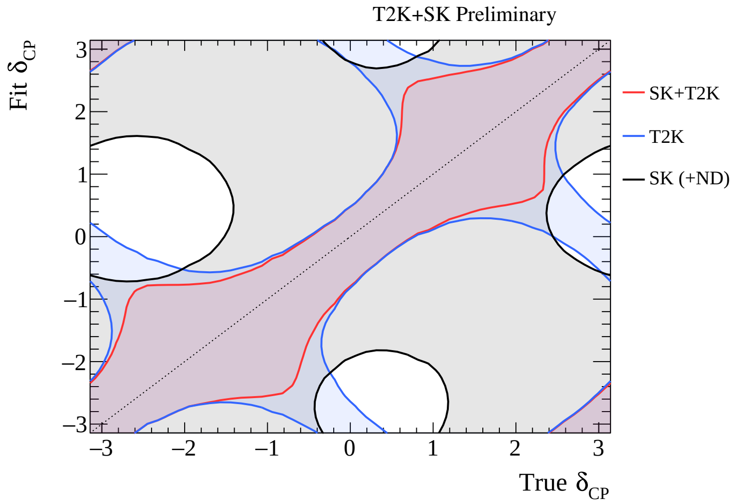
Another noticeable improvement by this joint analysis appears in the δ_{CP} fit accuracy. The T2K-only sensitivity is dominated by $\sin\delta_{cp}$ and hence has a degeneracy between $\sin(\phi)$ and $\sin(\pi-\phi)$. Although the SK atmospheric samples are overall less sensitive to δ_{CP}, they are able to break the degeneracy in T2K-only results through this joint analysis.

5. Conclusion and Prospects

A joint oscillation analysis combining the T2K accelerator and SK atmospheric neutrinos is conducted. A coherent analysis model is constructed and helps achieve an improved experimental sensitivity to δ_{CP} and MO. In this new model, the neutrino flux and detector systematic uncertainties from T2K and SK are applied without correlation, while a common cross section model is implemented for "sub-GeV" neutrinos and CCQE interactions. Additional uncertainties in various neutrino-nucleus interaction channels are also developed. At present, additional validations are ongoing to verify the robustness of this model. Upon their verification the first data results are expected soon. In the future, we look forward to expanding the joint analysis to the full SK data set. Meanwhile, the correlation between flux systematic uncertainties and between the detector uncertainty models are two of the major challenges and targets in the next iteration of this joint oscillation analysis.



(a) Sensitivity as a function of true δ_{CP} and assuming unknown MO



(b) 1σ confidence intervals as a function of true δ_{CP} with fixed NO

Figure 2: (a) Sensitivity to reject CP conservation as a function of true δ_{CP} and assuming unknown MO. (b) Confidence intervals computed by $\Delta\chi^2_{\text{true}} - \Delta\chi^2_{\text{fit,NO}} \leq 1$ for the shaded area. The diagonal line represents the case of perfect measurement. In both figures true NO is used, while the features are consistent when assuming true IO. This joint analysis has succeeded in resolving various degenerate effects of the oscillation parameters.

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