First joint analysis of Super-Kamiokande atmospheric and T2K accelerator neutrino data

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The Super-Kamiokande and T2K experiments present a combined analysis of their beam and atmospheric neutrino data. This analysis uses a common interaction model for events overlapping in neutrino energy and treats detector systematic uncertainties as correlated between the two data sets. The data from the two experiments are found to be compatible, and using a beam exposure of $19.7(16.3)\times10^{20}$ protons on target in (anti-)neutrino mode and 3244.4 days of atmospheric neutrino data, the analysis prefers the normal neutrino mass ordering and non-conservation of CP symmetry.

Introduction—Following the observation of neutrino oscillations [1], experiments now aim to fully characterize the three-flavor mixing paradigm described by the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix. Here, neutrino mixing is governed by three mixing angles (θ_{13}, θ_{23}, and θ_{12}), two mass splittings (Δm^2_{32} and Δm^2_{21}), and one Charge Parity (CP) violating phase ($\delta_{\rm CP}$). While some oscillation parameters have been precisely measured [2], others remain relatively unconstrained. In particular, the CP-violating phase, the ordering of the neutrino mass states (MO), and the octant of θ_{23} have not been determined experimentally. The magnitude of CP violation, which can be determined by the Jarlskog invariant [3, 4], $J_{\rm CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$, also remains unknown.

Experimental setup—The Super-Kamiokande (SK) experiment [5] measures atmospheric neutrino oscillations using a large multi-purpose water Cerenkov detector located in the Kamioka mine in Gifu, Japan. The detector has a 32 kiloton inner detector optically separated from a 2 meter thick outer detector, which mainly serves as a veto region. Detected atmospheric neutrinos, produced by the interaction of cosmic rays with nuclei in the Earth's atmosphere, include a mixture of neutrino flavor states, as well as a wide range of propagation baselines (15-13000km) and neutrino energies (MeV$\sim$TeV).

The Tokai-to-Kamioka (T2K) long-baseline neutrino experiment [6] measures neutrino oscillations over a baseline of 295 km using a primarily muon-(anti-)neutrino beam produced by the neutrino facility at J-PARC, located in Ibaraki, Japan. SK is T2K's far detector, located 2.5° off-axis, and measures neutrinos after oscillations. The beam neutrino flux and neutrino interaction cross sections are constrained by a suite of near detectors (T2K ND) situated 280 m downstream of the neutrino production target.

Motivation for a joint analysis—T2K's off-axis neutrino beam provides a narrow energy spectrum peaked at 600 MeV and a known direction for beam-induced events at SK, enabling a precise determination of $\sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$ using the "disappearance" channels ($\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$), and some constraint on the CP-violating phase and the MO via the lower statistics "appearance" channels ($\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$). The beam composition can be changed from primarily neutrinos to primarily anti-neutrinos by switching the polarity of electromagnetic focusing horns, providing the ability to compare neutrino and antineutrino oscillations. Its 295 km baseline probes the first atmospheric oscillation maximum at $L/E \sim 490$ km/GeV, but measurements are not significantly impacted by matter effects. This results in parameter degeneracies, notably between the lower and upper octants of θ_{23}, and between the MO and $\delta_{\rm CP}$. SK's atmospheric neutrino sample, on the other hand, provides a comparatively weak constraint on the atmospheric mixing parameters, due to limited information about the incoming neutrino direction, and a broader range of neutrino energies. However, upward-going neutrinos experience large matter effects, producing asymmetric oscillations between neutrinos and

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antineutrinos and providing sensitivity to both the octant of θ_{23} and the MO through the appearance channel at 2∼10 GeV. Atmospheric neutrinos provide a means of breaking the MO-$\delta_{\rm CP}$ degeneracy, complementing the MO sensitivity achieved at T2K through its lower energy $\overset{(-)}{\nu}_e$ appearance events. Additionally, common systematic uncertainties at SK can be better constrained in a joint fit than in the individual experiments, due to the addition of the T2K ND to the SK analysis and the large statistics atmospheric sample to the T2K analysis.

Analysis strategy—The analysis described here is based on previous analyses from the two experiments [7, 8], modified to produce a coherent joint analysis. Neutrino oscillation parameters are measured by comparing predictions for the rates and spectra of the beam and atmospheric neutrinos to observations performed at SK and making statistical inferences, following both frequentist and Bayesian approaches. The predictions are made using a model of the two experiments, covering fluxes, neutrino interactions, and detector response, with associated uncertainties. This model is built by unifying aspects of the two experiments' analyses when relevant, and using each individual experiment's approach otherwise.

Due to the similarities in neutrino energy spectra and event selections, T2K and low energy atmospheric events are described by a common neutrino interaction model. The remaining SK atmospheric events correspond to neutrinos of higher energies, for which the constraint on interaction uncertainties coming from the lower energy neutrino measurements at the T2K ND is not always directly applicable. As a result, for these samples, the same base interaction model is used for the initial simulation, but largely independent parameters are used for interaction systematic uncertainties. The neutrino flux models of the two experiments [7, 9, 10] are largely independent, with the only common source of systematic uncertainty coming from hadron production in proton collisions. Hadron production is tuned using different measurements in the two models: the SK atmospheric flux model uses atmospheric muon measurements [11, 12], whereas T2K's flux model uses measurements by the NA61/SHINE experiment [13]. The resulting uncertainties on flux predictions come from the uncertainties on those measurements and tuning procedures, and are considered to be independent between the two flux models. The neutrino events of the two experiments are observed in the same detector, and the correlated effects of detector systematic uncertainties on SK and T2K event samples were newly evaluated for the joint analysis.

Event selection—This analysis uses a total of 18 SK atmospheric and five T2K event samples, constructed as described in Refs. [8] and [14]. The event selections are based primarily on the number of reconstructed Cherenkov rings, the type of those rings, and the number of delayed Michel electron candidates. The ring types are either showering (e-like) or non-showering (μ-like) and are the basis of the separation between ν_e and ν_μ events. The T2K event selection targets events with little activity in the SK outer detector, so-called fully contained (FC) events, with a single Cherenkov ring. This topology primarily selects charged current quasi-elastic (CCQE)-like events, although in neutrino running mode an additional sample probes ν_e events containing a below-Cherenkov-threshold π^+ by requiring exactly one e-like ring and one Michel electron. Atmospheric neutrinos span a much wider range of energies, and, in the SK analysis, the FC sample is divided into sub- and multi-GeV categories based on the deposited visible energy in the detector. The SK analysis additionally includes events with significant energy deposition in the outer detector. Although there is a large kinematic overlap between the T2K beam samples and the FC single-ring sub-GeV atmospheric neutrino samples in SK, their respective event selections differ slightly. The selections remain the same as in the publications above with one exception: an additional cut is applied to both the SK FC and T2K samples to remove neutron contamination from the Michel candidates for each event. Both the SK and T2K event samples change by $\mathcal{O}(1\%)$ with the addition of this cut in both data and simulation.

Interaction model—Neutrino interactions are simulated with the NEUT generator 5.4.0 [15] using the same set of models as the T2K analysis described in Ref. [7]. The common "low-energy" uncertainty model used for the T2K and atmospheric SK FC sub-GeV samples is based on T2K's model, with additions to cover important uncertainties for the SK atmospheric analysis. Additional normalization uncertainties on the neutral current single π^0 model are introduced, which scale the resonant and coherent contributions separately, motivated by studies of MiniBooNE data [16, 17]. Given the greater importance of the uncertainty on the difference of cross-sections between ν_e and ν_μ for the atmospheric analysis, another uncertainty is added, based on the difference of the CCQE cross-section ratio $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ between the spectral function model [18] used in this analysis and new calculations using the Hartree-Fock model with Continuum Random Phase Approximation [19, 20]. The ability of this low energy model to describe the atmospheric sub-GeV data samples is evaluated by comparing its predictions using T2K's ND constraint to the observed data for the down-going part of those samples. The down-going events are mostly unaffected by oscillations, and can therefore be used to test the model while keeping the analysis reasonably blind. Good agreement with data is found for the samples targeting events without pions in the final state, but a significant data excess is seen in atmospheric samples targeting charged current single charged pion (CC1π^+) events where the pion is identified via a delayed Michel electron. An additional uncertainty for charged-current resonant interactions is introduced as a result. It changes the shape of the pion three-momentum spectrum by modifying the Adler angle [21] distribution, based on studies of theory-based [22, 23] and empirical modifications.

The model for the remaining SK samples (the "high-energy model") is based on the model used in the SK analysis, but shares the CCQE part with the low-energy model outside of high Q^2 (four-momentum transfer) parameters, due to similarities in the CCQE events' phase space outside of the high Q^2 region. SK and T2K's uncertainty models for resonant production and deep inelastic scattering events are very similar, the main difference being the existence of additional parameters and different nominal values in SK's analysis. For coherence, the single pion production parameters are set to the same values as in T2K, which come from studies of external data. This gives inflated uncertainties compared to SK's analysis. The model for pion final-state interactions is tuned to external data [24], as done by T2K.

Data from T2K's ND are used to constrain uncertainties on parameters from the low-energy model and the correlated part of the high-energy model, but not on the new uncertainties added for this analysis, or any other aspect of the high-energy model due to the lack of overlapping phase space between the near-detector selections and the non-sub-GeV atmospheric samples.

Detector uncertainty model—The same version of the SK event reconstruction algorithm [8] is used for the two experiments, to be able to derive correlations between their detector and reconstruction systematic uncertainties. Many of the detector uncertainties in both SK and T2K's analyses are estimated from comparisons between *atmospheric* data and simulation. For these, correlated uncertainties are constructed by evaluating the effects of variations of the detector parameters of the SK model on the number of events in the different samples of the two experiments simultaneously. Correlations between the reconstructed momentum scale uncertainty of the two experiments are found to have an impact on the constraint on Δm^2_{32} obtained in the data fit. Three of the four analyses described in the next section treat these parameters as correlated, while the fourth considers them uncorrelated. The remaining detector uncertainties from the reference SK and T2K analyses that are relevant for only one of the experiments are applied to the relevant samples. An additional systematic uncertainty is introduced for the sub-GeV samples targeting CC1π^+ events. It allows single ring single Michel electron events with low lepton momentum to migrate between ν_e-like and ν_μ-like. The size of this uncertainty covers the excess in data observed for the down-going CC1π^+ ν_e-like events at low momentum.

Oscillation analysis—Two Bayesian and two frequentist analyses based on the model described above but with differences in technical implementation, binning, and statistical methodology are used to fit the data. To constrain uncertainties using the T2K ND, one analysis performs simultaneous fits of the T2K ND, T2K far detector and SK atmospheric data, while the other ones use a covariance matrix to encode T2K's ND constraint on systematic parameters when fitting the events observed at SK. The Bayesian analyses use Markov Chain Monte Carlo methods to evaluate marginal likelihoods for the parameters of interest, while the frequentist analyses compute the profile likelihood on a fixed grid of values of the oscillation parameters of interest. For atmospheric oscillation probability calculations, path-dependent density averaging of the matter effect based on a 4 layer approximation of the PREM model [25] is used, and the fast atmospheric oscillations at low energy are smeared using different techniques depending on the analysis. The path-dependence yields more precise oscillation probabilities than the conventional approximation assuming layers of constant density. Finally, all analyses utilize a binned log-likelihood test-statistic assuming Poisson-distributed bin contents plus Gaussian penalties for the systematic parameters. The anti-neutrino measurement of θ_{13} by reactor experiments [2, 26–29] is used as an external constraint $\sin^2 2\theta_{13} = 0.0853 \pm 0.0027$.

Validation—Simulated datasets [7] are used to test the robustness of the analysis to effects not included in the base systematic uncertainty model. They are generated using alternative models, and fitted using the nominal model to measure how the obtained p-values and constraints on oscillation parameters would be affected by having assumed the wrong model. Fourteen such simulated datasets are considered, corresponding to alternative neutrino interaction models and data-driven effects at both T2K ND and SK. These studies are used to estimate, amongst others, how much the data excess observed in the atmospheric down-going CC1π^+ samples would bias the results if it was due to unknown systematic effects. Some of the simulated datasets produce a visible shift in the preferred values for Δm^2_{32}. The uncertainty on Δm^2_{32} is inflated by 3.6×10^{-5} eV$^2/c^4$ to account for these effects.

Dataset— The same T2K dataset as in the reference analysis [7] is used, corresponding to T2K runs 1 to 10, and exposures of 19.7×10^{20} and 16.3×10^{20} protons on target in neutrino and anti-neutrino running modes, respectively. The atmospheric dataset is slightly increased compared to the reference analysis [8] to include the full Super-Kamiokande IV period (2008-2018), corresponding to a total live-time of 3244.4 days.

Bayesian results—The Bayesian analyses assume uniform priors on $\delta_{\rm CP}$ or $\sin\delta_{\rm CP}$, $\sin^2\theta_{23}$, Δm^2_{32}, and the MO. They find a preference for near-maximal CP-violation, normal ordering, and a weak preference for the upper octant (Table I). SK and T2K data prefer different octants which leads the joint analysis to have a weaker octant constraint than the individual experiments and a higher probability for maximal mixing, while for the CP-violating phase, both experiments favor similar values (Figure 1). The exclusion of CP symmetry is quantified by checking whether the CP conserving values of $J_{\rm CP}$ and $\delta_{\rm CP}$ are included in highest posterior density credible intervals corresponding to different standard fractions of the posterior probability (Figure 2). The significance for a given value is defined as the largest tested fraction for which this value is not included in either of the intervals obtained by the two Bayesian analyses. The results are summarized in Table II.

TABLE I. Bayes factors obtained by one of the Bayesian analyses using either the full dataset or samples from only one experiment. Values obtained by the second analysis for the combined dataset are shown in parentheses.

	SK only	T2K only	SK+T2K
Upper/lower octant	0.47	3.65	1.56 (1.78)
Normal/inverted ordering	1.89	4.96	8.89 (7.33)

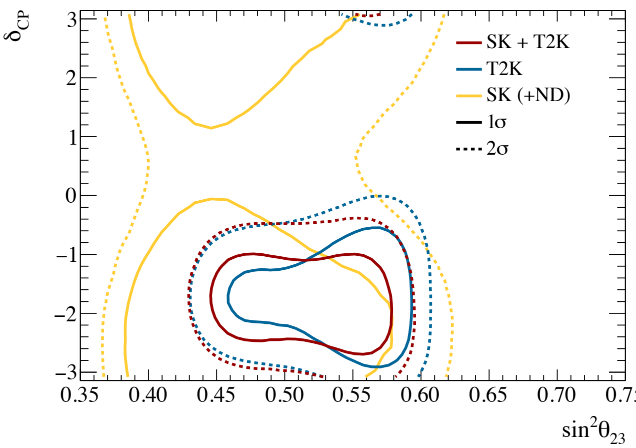

FIG. 1. The ($\sin^2\theta_{23}$, δ_{CP}) credible regions obtained with the SK, T2K, and combined datasets. The MO is marginalized over and a prior uniform in δ_{CP} is used.

TABLE II. Significance of the exclusion of different CP conserving values of J_{CP} and δ_{CP} by the Bayesian analyses. Values in parentheses indicate how the significance changes when taking into account possible biases identified using the simulated datasets.

Value tested	Prior uniform in	
	δ_{CP}	$\sin(\delta_{CP})$
$J_{CP} = 0$	$>2\sigma$ ($>2\sigma$)	$>2\sigma$ ($>90\%$)
$\delta_{CP} = 0$	$>2\sigma$ ($>2\sigma$)	$>2\sigma$ ($>2\sigma$)
$\delta_{CP} = \pi$	$>2\sigma$ ($>2\sigma$)	$>90\%$ ($>1\sigma$)

Frequentist results—Ensembles of pseudo-experiments are constructed to evaluate the frequentist significance of the CP and MO results, taking into account statistical fluctuations and randomizing the values of nuisance oscillation and systematic parameters according to their posterior [30] and prior probability distributions respectively. The significance of the exclusion of CP conservation (CPC) is estimated using the log-likelihood ratio of best CPC ($\sin\delta_{CP} = 0$) vs. best CP-violating hypotheses as a test-statistic. An alternative hypothesis is also

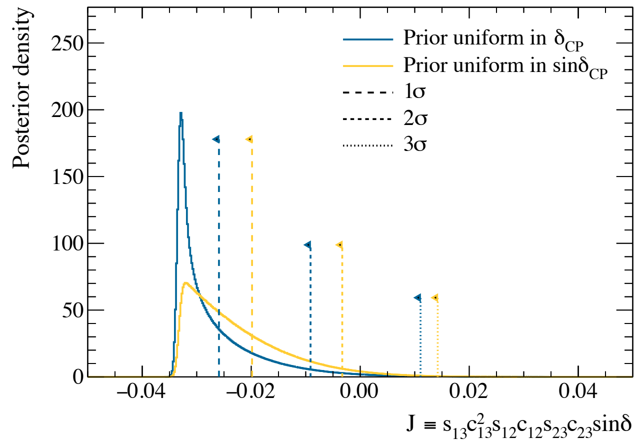

FIG. 2. The posterior density for the Jarlskog invariant with credible intervals overlaid, marginalized over both MOs, and assuming a uniform prior in either δ_{CP} or $\sin\delta_{CP}$.

tested, "Posterior δ_{CP}", for which true δ_{CP} values are sampled from the posterior distribution. For the neutrino MO, the log-likelihood ratio of best normal and inverted ordering hypotheses is used as a test-statistic (Figure 3).

The obtained p-values are summarized in Table III. CP conservation is disfavored with a lower p-value ($p = 0.037$) than when using only the T2K data ($p = 0.047$). The inverted ordering is disfavored while good agreement with the normal ordering hypothesis is found, resulting in a CL_s parameter [31] for the inverted ordering of 0.18. The distribution of the MO test-statistic depends on the assumed values of $\sin^2\theta_{23}$ (for SK) and δ_{CP} (for T2K). The p-value for the inverted ordering varies between 0.05 and 0.08 when assuming different fixed true values for $\sin^2\theta_{23}$ and δ_{CP} over the range of their 90% confidence intervals. The 68.3% confidence intervals obtained using the Feldman–Cousins method [32], with other oscillation parameters including the MO treated as nuisance parameters, are $[-2.71, -1.03]$ for δ_{CP} and $[0.443, 0.574]$ for $\sin^2\theta_{23}$.

TABLE III. Frequentist p-values for the different CP and MO hypotheses. The most conservative of the two values obtained by the frequentist analyses is reported, and for the disfavored hypotheses, the value up to which the p-value could increase due to biases seen in simulated data studies is given in parentheses.

Hypothesis	p-value
CP conservation	0.037 (0.050)
Posterior δ_{CP}	0.75
Inverted ordering	0.079 (0.080)
Normal ordering	0.58

Goodness of fit—The Bayesian analyses find reasonable posterior predictive p-values [33] using both the event spectra ($p = 0.24$) and total event counts ($p = 0.19$). The p-values for the individual T2K samples agree

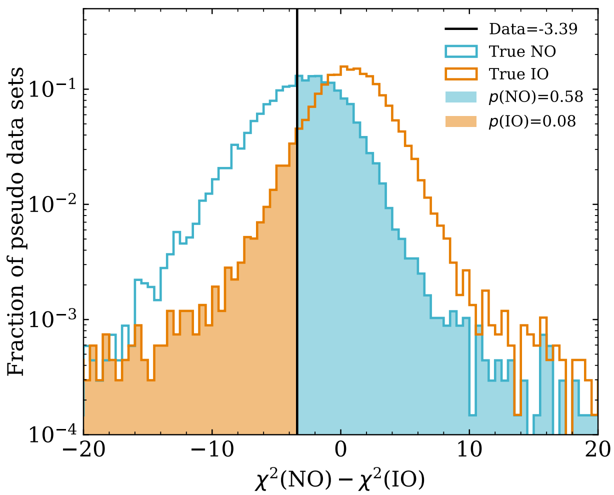

FIG. 3. Distribution of the MO test statistic under true normal and inverted ordering hypotheses. The filled areas to the left (right) of the data result indicate the p-values for the inverted (normal) hypotheses.

with the reference T2K analysis [7] up to small differences coming predominantly from model changes rather than the preferred values of the oscillation parameters or the addition of SK's atmospheric samples. The frequentist p-values [34] additionally show good consistency between the values of the systematic parameters favored by the T2K ND and atmospheric data ($p = 0.19$), as well as between the atmospheric and beam samples ($p = 0.24$).

Discussion—The SK and T2K datasets favor similar values for the CP phase, close to maximal CP violation, and both show a preference for the normal MO. As a result, the combined analysis finds increased preferences for non-conservation of CP symmetry and the normal ordering, although the statistical significance of these preferences remains limited. When looking directly at the exclusion of CPC through the presence of $J_{\rm CP} = 0$ in credible intervals or frequentist p-values, an exclusion at the 2σ level is found. However, this level of significance is not robust against potential weaknesses of the uncertainty model, as tested using simulated datasets. The problematic model in both cases assumes that the data excess observed in down going low energy samples targeting CC1π^+ events is fully due to an unknown systematic effect. This indicates a need to improve the modeling of CC1π^+ interactions with a low-momentum pion for future analyses.

Conclusion—The SK and T2K collaborations have produced a first joint analysis of their data. The results show an exclusion of the conservation of CP symmetry close to the 2σ level, a limited preference for the normal ordering, and no strong preference for the θ_{23} octant. Further combined analyses using a larger data sample and new analysis developments from SK and T2K are expected to bring increased sensitivity.

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