PROCEEDINGS OF SCIENCE

T2K and T2K+SK results

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Tokai-to-Kamioka (T2K) is a long-baseline neutrino oscillation experiment which utilizes a neutrino beam produced at the Japan Particle Accelerator Research Center. The composition and energy of the oscillated neutrino spectrum are measured using the Super-Kamiokande (SK) water Cherenkov detector located 295km downstream. Significant updates have been made to previous oscillation analyses, resulting in charge-parity (CP) violation being excluded at 90% confidence level. In addition, a T2K+SK joint analysis of beam and atmospheric neutrinos has been performed which strengthens the exclusion of CP-violation to 1.9σ. The Bayes factor for normal hierarchy preference, as calculated by the joint analysis, is found to be $B(NH/IH) = 8.98$.

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1. Introduction

The PMNS matrix [4] describes the flavour-mass mixing of active neutrino's mass states and weak flavour eigenstates. It can be parameterized by three mixing angles, $\theta_{ij}(i \neq j,\ \ i, j = 1, 2, 3)$, two mass squared splitting terms, Δm^2_{21} and Δm^2_{31}, where $\Delta m^2_{ij} = m^2_i - m^2_j$, and a charge-parity (CP) violating term, δ_{CP}. Strong constraints have been placed on θ_{12}, θ_{13}, Δm^2_{21}, and $|\Delta m^2_{32}|$ by a combination of accelerator, reactor and atmospheric neutrino oscillation experiments [4]. However, several questions are left unknown; the ordering of neutrino states, the octant of θ_{23}, and the value of δ_{CP}. The ordering of neutrino states is often called the "hierarchy problem". It relates to the sign of Δm^2_{32}, with the normal hierarchy resulting in a positive value and the inverted hierarchy having a negative value.

2. The Tokai-to-Kamioka (T2K) and Super-Kamiokande (SK) experiments

The Tokai-to-Kamioka (T2K) experiment is a long-baseline neutrino oscillation experiment in Japan [1]. The J-PARC accelerator facility produces a muon neutrino beam of average energy of 600MeV. Three focusing horns can select a predominantly neutrino or antineutrino beam, depending upon the polarity of the horn current. A suite of near detectors is situated 280m downstream of the target and characterizes the product of unoscillated flux and cross-section in the beam. The Super-Kamiokande (SK) detector [3] is located as the far detector with a baseline of 295km. It is a 50kTon water Cherenkov detector that measures the charge and flavour of the lepton emitted from the neutrino-nucleus interaction in the detector (mainly charged current quasi-elastic interactions). In addition to beam neutrinos, SK also observes neutrinos generated by cosmic ray interactions in the atmosphere.

The far detector is situated 2.5° off-axis, narrowing the spectrum of neutrino energies. The peak energy of $600MeV$ energy neutrinos, combined with the baseline of the far detector, is optimized to ensure maximum oscillation probabilities of beam neutrinos at SK. The ND280 near detector is situated at the same off-axis angle as SK and is comprised of an electromagnetic calorimeter, two fine-grained scintillating detectors, and three time-projection chambers. This detector is situated within a 0.2T magnetic field which allows sign-selection of positively or negatively charged particles.

3. The oscillation analysis

Due to the ability to differentiate electron and muon final states in the far detector, T2K can study both muon (anti-)neutrino disappearance and electron (anti-)neutrino appearance. Additionally, the asymmetry of the oscillation between neutrino and antineutrino oscillations can be compared. Consequently, this means the T2K experiment is most sensitive to $\sin^2(\theta_{23})$, Δm^2_{32}(NH)/Δm^2_{31}(IH) and δ_{CP}. The near and far detector data can be fit sequentially or simultaneously, depending on the analysis strategy. In either strategy, a likelihood is built by comparing a model prediction and the measured data which provides a best-fit value and uncertainty on the oscillation parameters. The model prediction is comprised of several parts; beam neutrino flux prediction, neutrino-nucleus interaction model, and detector modelling (both near and far). The flux and cross-section models include constraints from external data sets whilst the detector models use calibration data to ensure the accuracy of the model. In addition to this, external constraints are placed on the oscillation parameters that the T2K experiment is not sensitive to; $\sin^2(\theta_{13})$ from reactor experiments, and solar experiments constraints on $\sin^2(\theta_{12})$ and Δm^2_{12}.

The near detector data is split into 22 different muon-neutrino selections based on interaction vertex, target, horn current and reconstructed final state topology. The fit of the near detector data provides a constraint on the flux and cross-section systematic parameters used within the respective models. The far detector data samples are broken down by reconstructed neutrino flavour, horn current and the presence of a charged pion in the final state. The far detector samples are represented in a combination of bins in reconstructed neutrino energy and direction of the outgoing lepton.

There have been several updates since the last T2K oscillation analysis [1]. The neutrino-mode data has been increased by 10%. An additional sixth sample at the far detector has been added which targets muon-flavour events in neutrino mode with a pion in the final state. This corresponds to a 40% increase in the muon-neutrino statistics. Despite this increase, the majority of events in this sample have true neutrino energy which is above the oscillation maximum, and thus have a small impact on the oscillation parameter sensitivity. However, this sample allows additional validation of the background modelling and constraints on the systematic parameters. There have also been improvements made to the treatment of the detector systematics in the far detector as well as including additional cuts to distinguish decay electrons from neutrons in far detector samples.

4. Latest results of T2K oscillation analysis

Using the methods outlined in section 3, the results of the T2K Run 1 $\sim$ 11 oscillation analysis results are presented below. Figure 1 illustrates the number of electron-neutrino appearance candidates, comparing the number of candidates in neutrino and antineutrino beam mode. Several predictions for varying values of $\sin^2(\theta_{23})$, δ_{CP} and mass hierarchy. The data prefers the region of $\delta_{CP} \simeq -\pi/2$, $\sin^2(\theta_{23}) \simeq 0.55$ and the normal hierarchy. Figure 2 illustrates both the $\Delta\chi^2$ distribution as a function of δ_{CP} obtained for each mass hierarchy, and the posterior probability in terms of Δm^2_{32}. Due to the non-Gaussian likelihood curves, Feldman-Cousins studies are performed to determine the critical χ^2 values at which the confidence intervals are placed on δ_{CP}. CP0-conserving values of δ_{CP} are excluded at 90%C.L. and close to a 2σ level. Additionally, several checks are performed to ensure the analysis is robust to model choices. Specifically, several studies were performed to check the flux and cross-section models since no model fully reproduces all known external data sets. Fake data is simulated from each alternative model and fit. A bias of $3.1 \times 10^{-5}\text{eV}^2/\text{c}^4$ is found from these alternative model studies and is taken into account when calculating the uncertainty of Δm^2_{32}. Consequently, the best fit of $\Delta m^2_{32} = 2.51 \times 10^{-3}\text{eV}^2$ with the allowed 1σ region comprising of $[2.42, 2.58] \cup [-2.56, -2.54]$.

The fraction of the posterior probability in each octant and hierarchy is provided in Table 1. The Bayes factor for the normal hierarchy and upper octant is 3.3 and 2.6, respectively.

5. Joint analysis with atmospheric neutrinos measured at Super-Kamiokande

In addition to the T2K-only analysis documented in section 4, T2K has released two joint analyses with the beam neutrinos from NOνA (T2K+NOνA) [5] and atmospheric neutrinos measured

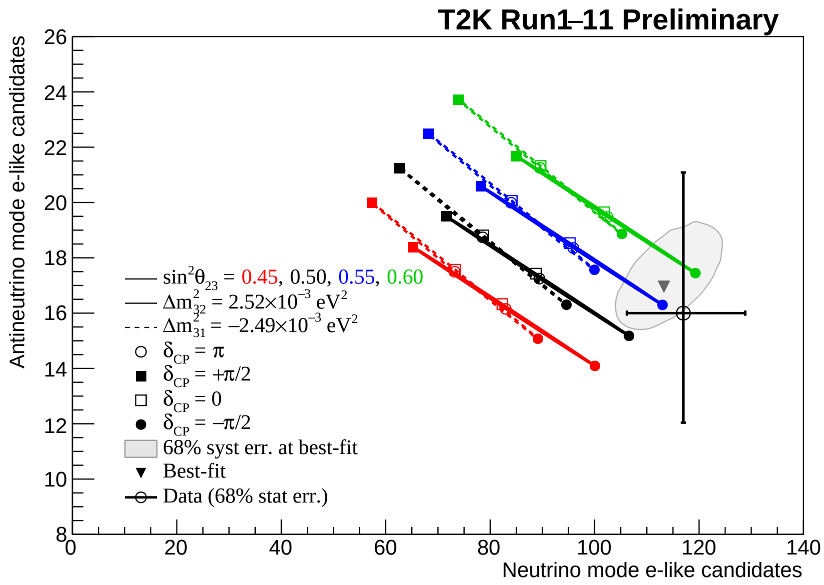
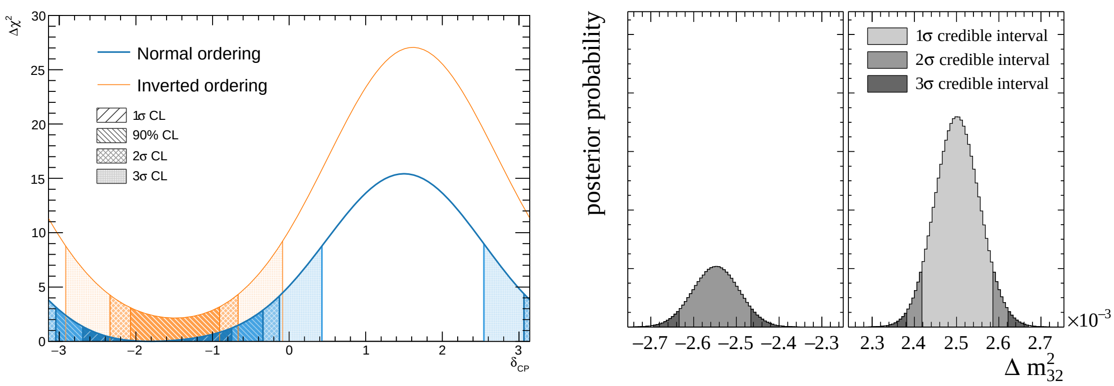


Figure 1: The variation of the ν_e and $\bar{\nu}_e$ event rates, on the x-axis and y-axis respectively, for changes in the oscillation parameters. Different colours represent different true $\sin^2(\theta_{23})$, marker styles represent different true δ_{CP}, and solid (dashed) lines true NH (IH). The latter two parameters have degenerate effects on the event rates. Data is shown with statistical error.



(a) δ_{CP} **(b)** Δm^2_{32}

Figure 2: The $\Delta\chi^2$ confidence limit statistics on δ_{CP} and the posterior probability distribution as a function of Δm^2_{32} from the Run1 ~ 11 T2K oscillation analysis.

by Super-Kamiokande (T2K+SK) [2] collaborations. The T2K+SK analysis utilizes the T2K Run 1 ~ 10 analysis [1] and the SK-IV analysis [3]. This corresponds to 3.6×10^{21} protons on target for the beam analysis and 3244.4 days of live time for the atmospheric analysis.

As seen in Figure 1, the effect of varying δ_{CP} and the unknown mass hierarchy result in a similar modification to the ν_e and $\bar{\nu}_e$ appearance probabilities, resulting in a degeneracy. Upward-going atmospheric neutrinos experience matter effects from the high-density regions within the

	$\sin^2(\theta_{23}) < 0.5$	$\sin^2(\theta_{23}) > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00

Table 1: Percentage of the posterior probability in each mass ordering and the octant in the T2K oscillation analysis.

earth. This results in unique resonance signatures at $E_\nu \sim O(1)$GeV in either of the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ channels depending on the true mass hierarchy. The amplitude of this effect depends on the value of $\sin^2(\theta_{23})$ and is mostly uncorrelated with the value of δ_{CP}. Thus a simultaneous oscillation analysis of beam and atmospheric neutrinos can improve the constraints on the unknown parameters.

A consistent systematic model has been constructed for the joint oscillation analysis. It is based on the models used in each experiment. The beam and atmospheric flux uncertainties are uncorrelated due to the differing approaches to constrain the systematic uncertainties. A correlated detector model is implemented by simultaneously evaluating the effects of the detector parameter variations on both the beam and atmospheric samples. The interaction model is split into two halves; "low-energy" and "high-energy". The low-energy uncertainty model is applied to both beam and sub-GeV atmospheric samples. It is based on the T2K model with additional to cover uncertainties in the atmospheric samples. Constraints from T2K's near detectors are applied to this low-energy model. The high-energy model has been taken from the SK analysis with minor additions included to cover additional CCQE uncertainties. More details of the systematic model can be found in [2].

6. Results of the Tokai-to-Kamioka and Super-Kamiokande joint analysis

The methodology used in the joint analysis follows that outlined in section 3 but includes the likelihood term from the atmospheric samples and penalty term from the additional systematic parameters. The credible intervals, provided as a function of δ_{CP} and $\sin^2(\theta_{23})$ are provided in Figure 3. The joint analysis has tighter constraints on δ_{CP} than either experiment alone and the preference to the octant of $sin^2(\theta_{23})$ is reduced compared to the T2K only analysis. This is due to the opposite preference of octant in both experiments. The conclusion is that the CP-conserving values of δ_{CP} are excluded at a 1.9σ to 2.0σ level.

Figure 4 illustrates the distribution of the χ^2 statistic between the normal and inverted hierarchies, as calculated by a frequentist analysis. The fraction of pseudo-datasets for models created assuming the true normal and inverted hierarchy are illustrated in blue and orange respectively. The p-value assuming an inverted hierarchy is 0.08. The corresponding Bayes factor, as calculated by a Bayesian analysis, is calculated to be $B(NH/IH) = 8.98$, indicating a preference for the normal hierarchy.

7. Future plans for Tokai-to-Kamioka experiment

In addition to the updates presented within this document, there have been many updates to the suite of near detectors. The dedicated π^0 detector in ND280 has been replaced with a

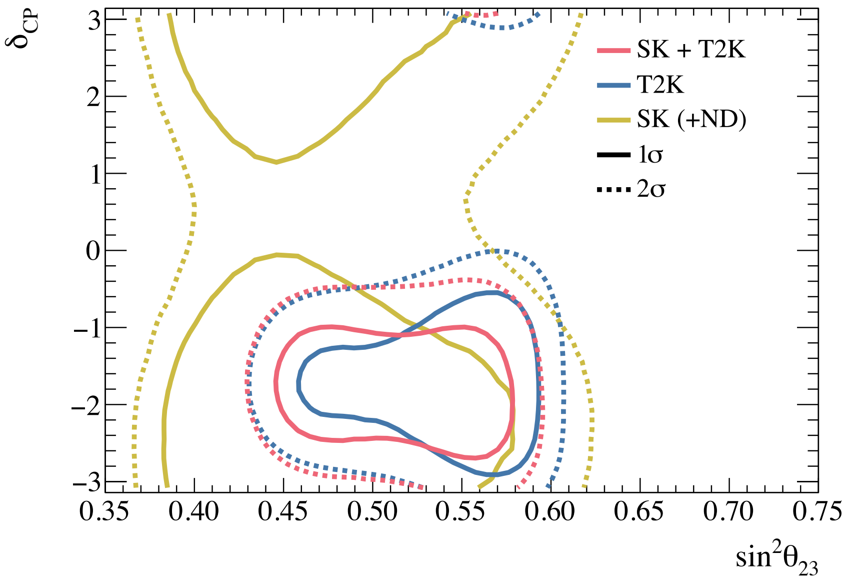


Figure 3: The $(\sin^2(\theta_{23}), \delta_{CP})$ credible regions obtained with the SK, T2K, and combined datasets. The MO is marginalized over and a prior uniform in δ_{CP} is used.

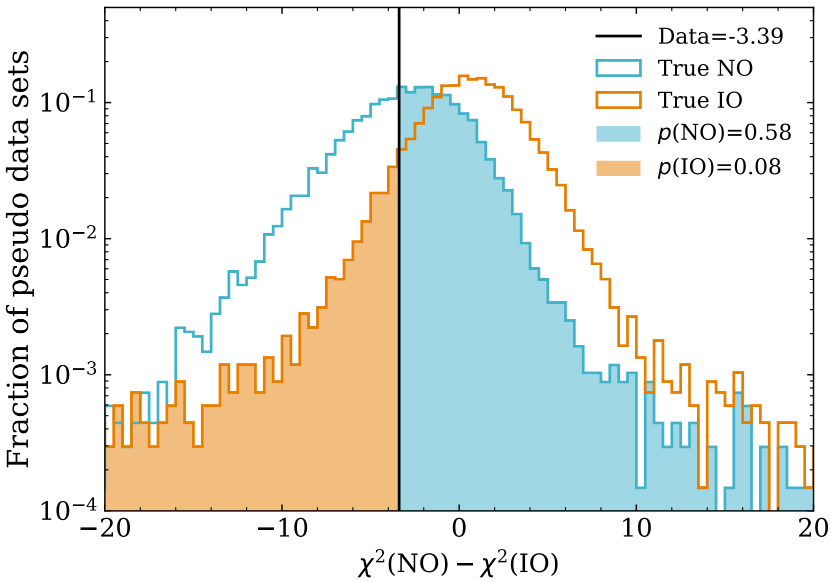


Figure 4: Distribution of the mass hierarchy test χ^2 statistic under true normal and inverted hierarchy hypotheses. The filled areas to the left (right) of the data result indicate the p-values for the inverted (normal) hypotheses.

three-dimensional scintillating cube detector sandwiched between two high-angle time projection chambers. This new scintillator target detector will have several benefits when compared to the previous detector design; improved efficiency for selecting muons with a larger angle to the beam, lower detection threshold for low-momentum protons, and increased neutron-tagging performance. The full suite of new sub-detectors is currently under commission and the first tracks across all new sub-detectors were first observed in June 2024. Beyond the improved detector technology, the T2K experiment aims to collect 10×10^{21} protons-on-target by the end of 2027. Current beam power has already been increased to 800kW and the collaboration is well on the way to reaching this goal.

8. Conclusion

The Tokai-to-Kamioka (T2K) collaboration has significantly improved previous oscillation analyses; using additional data, improving the detector systematics treatment, and including additional sample selection cuts to improve decay-electron and neutron separation. These updates exclude charge parity (CP) conserving values of $\delta_{CP} = 0, \pi$ at 90% confidence level. The Bayes factor for the normal hierarchy and upper octant is 3.3 and 2.6, respectively. In addition, T2K has also performed joint oscillation analyses with the NOνA [5] and Super-Kamiokande (SK) [3] collaborations. A consistent systematic model was created for the T2K+SK joint analysis, which includes correlations in the detector and interaction model between atmospheric sub-GeV and beam neutrino events. This joint analysis found a Bayes factor for the normal hierarchy of $B(NH/IH) = 8.98$ and CP conserving values of δ_{CP} being excluded at 1.9σ to 2.0σ level.

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