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Latest Results from the T2K and NOvA Experiments

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T2K and NOvA are the two current long-baseline neutrino experiments which exploit both the neutrino and antineutrino beams in Japan and US, respectively, to perform precision measurements of neutrino oscillation parameters Δm^2_{32}, $\sin^2\theta_{23}$ and the CP-phase δ_{CP}. The independent oscillation analyses by either experiments slightly prefer the normal ordering of the mass hierarchy and the upper octant of $\sin^2\theta_{23}$ with a nearly maximal CP-violating phase. In this document, the latest results for the measurement of PMNS parameters are presented along with the status of the combined analysis fit of the two experiments.

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1. Introduction

T2K and NOvA are currently the two long-baseline neutrino experiments that have been running for more than a decade and have achieved multiple milestones along the path of understanding neutrino oscillations.

The T2K experiment in Japan uses a (anti)neutrino beam peaking around 0.6 GeV across a baseline of 295 km, while the NOvA uses a beam of 2 GeV over 810 km, as depicted in Fig. 1. Unique in their detection technologies, especially at the far detector end, the two experiments have been measuring the neutrino oscillation parameters with increasingly improved precision with every cumulative beam time data. The T2K far detector uses the Water Cherenkov detection technique with a 50 kt target of water, while the NOvA far detector of 14 kt target uses liquid scintillator filled inside plastic cells.

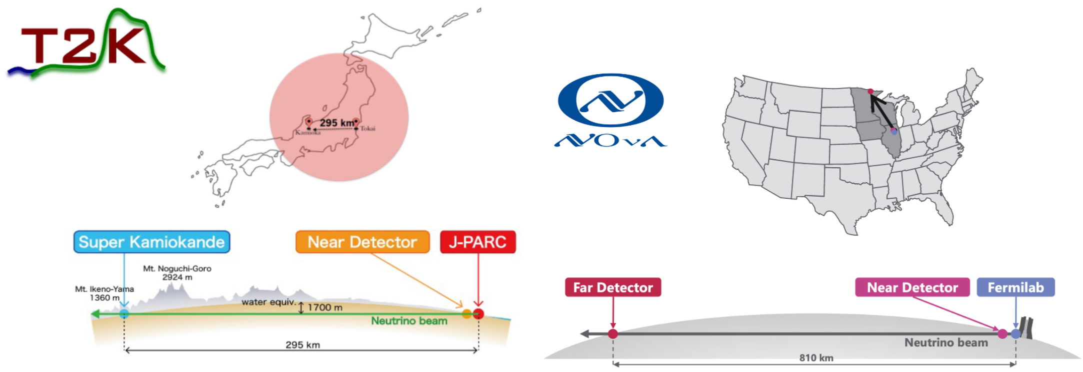

Figure 1: Schematic diagram of the two long-baseline experiments, T2K (left) and NOvA (right)

The three-flavor neutrino oscillation is mainly described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix, which relates the mass eigenstates with the neutrino flavor eigen states [2, 3]. Most of the parameters therein have been determined with significant precision so far by several experiments. The still remaining important questions are the determination of the CP phase (δ_{CP}), the ordering of the neutrino mass hierarchy (Δm^2_{23}), and the octant and precision of the third mixing angle (θ_{23}). This requires one to also ensure minimum systematic uncertainties in the experiments, which are addressed through a number of contributing factors, like the flux, the neutrino interaction models, and the constraints from the near detectors, to name a few.

The two long baseline neutrino experiments measure the neutrino oscillation parameters, with the near detectors observing/monitoring the neutrino beam closer to the source and the far detectors measuring the rate of events after oscillation. The neutrino beam is produced by the proton beam (30 GeV for T2K and 120 GeV for NOvA) incident onto a graphite target, which produces a spray of hadrons. This is followed by the selection of mainly charged pions by magnetic horns and letting them decay into muons and neutrinos. All charged particles are then dumped or absorbed, allowing the neutrinos to only beam through, as known as the neutrino or antineutrino beam.

2. The T2K Experiment

T2K (Tokai to Kamioka) [1] is a long-baseline neutrino experiment located in Japan that sends muon-(anti)neutrino beams, produced from 30 GeV protons at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai to Kamioka, along the 295 km baseline. The 2.5°off-axis beam peaks around 0.6 GeV. The near detectors for this experiment are located 280 m downstream from the source at J-PARC in Tokai, while the water-Cherenkov detector, Super-Kamikande at Kamioka, plays the role of the far detector for studying neutrino oscillations.

The results presented in this report use data from T2K beam runs 1-10, which correspond to 3.6×10^{21} protons on target (POT).

2.1 Near Detectors

The near detectors (ND) of the T2K primarily comprise of the on-axis INGRID detector and a composite tracking detector called "ND280" placed 2.5° off-axis of the neutrino beam, 280 m from the source.

The detector along the axis of the beam, built out of alternating scintillator-iron layers (INGRID) monitors the incident neutrino beam and its stability. The off-axis near detector suite (ND280) comprises of a magnet, two fine-grained detectors (FGD1: scintillators, FGD2: scintillator-water layers) in between three time projection chambers (TPCs) to act as the tracker, the Electromagnetic Calorimeter (scintillator-lead), the Pi-Zero detector (scintillator-water bags), and the Side-Muon Range Detector (scintillator plates). The magnetic field of 0.2 T helps in charge identification of the particles. The ND280 thus plays an important role in constraining the uncertainties in the interaction modelling as well as the intrinsic "wrong sign" contaminations (i.e. $\bar{\nu}_\mu$s in a ν_μ-beam or vice versa[1]).

The dominant interaction type in the energy range for T2K, is the charged-current quasi-elastic reaction (CCQE). Other charged-current interactions are also present, mainly the resonant pion production (CCRES) and deep inelastic scattering (CCDIS) channels.

The events in the near detector are classified according to the topology based on the reconstructed pion multiplicity. Selections were done with mainly three types of topologies: the charged current no-pion (CC0pi) events, the CC1pi (events containing only one pion track besides the lepton), and the CC-others (events containing multiple tracks), which are enriched in the CCQE, CCRES, and CCDIS channels, respectively. However, improvements in the selection processes have been made by implementing proton/gamma tagging methods [5], criteria based on the energy and charge depositions, likelihood ratios, and electromagnetic shower topologies, all resulting in an increase in the purity of the samples by 5-10%. Five types of topological classifications are hence used: $CC0\pi0p0\gamma$, $CC0\pi1p0\gamma$, $CC1\pi^+0\gamma$, $CCother0\gamma$, and CC-PhotonShower. A total of 22 such samples (FGD1, FGD2, both modes, and wrong-sign component for the anti-neutrino mode) were used for this analysis, a few of which are shown in Fig. 2.

[1] the latter (ν_μs in $\bar{\nu}_\mu$s) being significant, and the SuperK being a non-magnetised detector, contraining the wrong sign component is also important

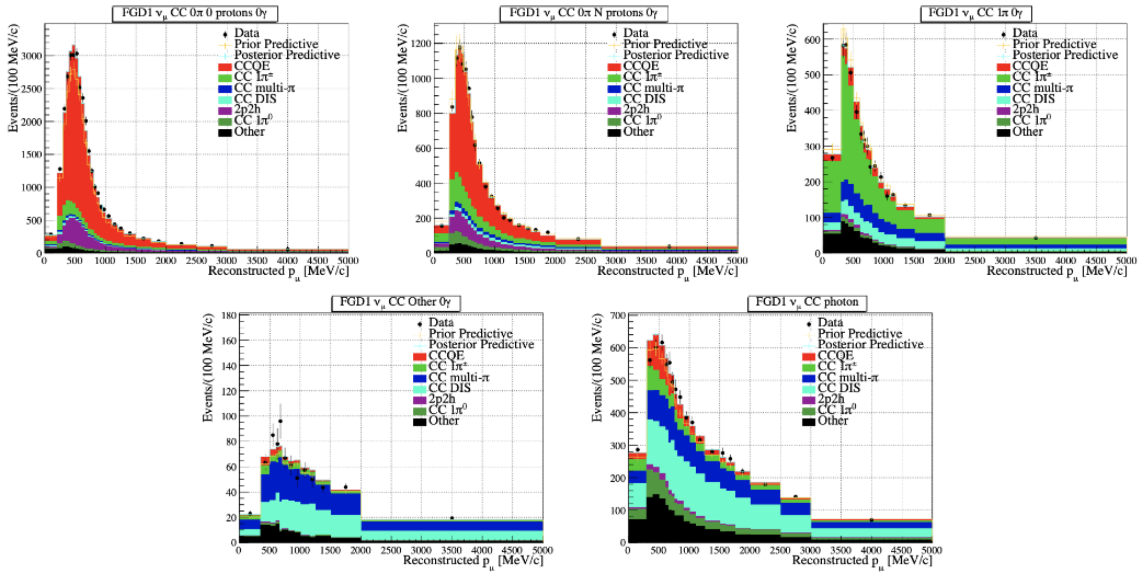

Figure 2: The five neutrino mode ND samples events distributions in one of the FGDs.

2.2 Far Detector

SuperK, the far detector (FD) of T2K, is a water Cherenkov detector located 2.5° off-axis, with 50 kt of water target. The detector is read out by ~11k PMTs, and the muons, electrons, and π^0s are identified from the ring-topologies. A likelihood separation method well identifies the muons from electrons. The mis-identification of the particles (PID) is as low as $< 1\%$ at 1GeV and records an energy resolution of $\Delta E/E$ ~10% for the QE events. The FD fiducial volume considered for this analysis is more than 22.5 kt.

Five single-ring samples and one new multi-ring sample [6] have been used for this analysis, as listed in Table 1.

Table 1: Details of the five single-ring samples and the new multi-ring sample used to classify the far detector samples.

	e-like samples	μ-like samples
ν-mode	1 Ring + 0 decay-e	1 Ring + 0/1 decay-e
ν-mode	1 Ring + 1 decay-e	Multi-Ring (1 Ring + 2 decay-e; 2 Ring-events)
$\bar{\nu}$-mode	1 Ring + 0 decay-e	1 Ring + 0/1 decay-e

2.3 Oscillation Results

The oscillation analysis is done by fitting the far detector samples, while using the ND samples to constrain the uncertainties. An extended binned likelihood fit to the ND sample as a function of muon kinematics is made to constrain the predicted number of events. The analyses are done with two independent methods, where the ND and FD data fits are done either simultaneously (Bayesian approach) or sequentially (Feldman-Cousins or Frequentist approach), details of which can be found in Ref. [4].

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The best-fit value for θ_{23} is found to be in the upper octant, with the lower octant still allowed at the 68% CL, shown in Fig. 3-left. The CP-conserving values of δ=0 and δ=π are outside of 90% CL intervals across both orderings of mass hierarchies, as shown in Fig. 3-right. The best-fit point with the current oscillation analysis status is found to be around $\delta_{CP} \approx -\pi/2$ for both orderings.

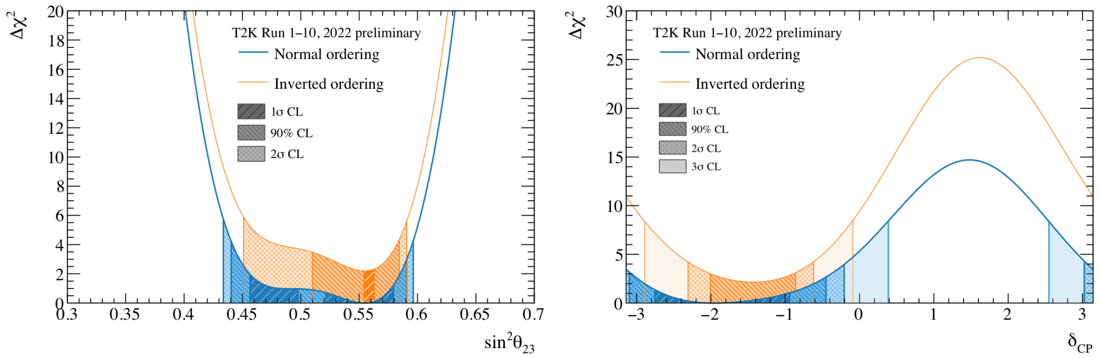

Figure 3: $\Delta\chi^2$ surface for θ_{23} and $\delta_{\rm CP}$ with Feldman-Cousins CL intervals for both mass orderings.

Searches for potential CP violation by looking at the posterior probability and credible intervals for the Jarlskog invariant, $J_{CP}(\equiv \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP})$, also showed that the value of this invariant being zero is excluded at more than 2σ credible level, thus excluding the CP conservation values. More details of the oscillation results may be found in Ref. [4].

3. The NOvA Experiment

The NOvA long baseline experiment in the United States, studies neutrino oscillations using the (anti)neutrino beam peaking at 2 GeV produced by the NuMI beam facility at the Fermilab, Chicago, and the far detector 810 km away at Minnesota, by the Ash river. The far detector has a 14 kt target mass, composed of plastic cells filled with liquid scintillators, while the near detector bearing similar composition in 0.3 kt is placed a km away from the source. The near detector being 100 m underground observes less cosmic muon background, in comparison to the far detector, which is on the surface.

Data corresponding to a total of 3.7×10^{21} POT have been used for this analysis. Information presented in this section are taken from Refs. [7–9].

3.1 Near and Far Detector Samples

The neutrino events are identified with a convolutional neural network (CNN), and the interaction types are classified by topologies. Data-driven techniques are used to improve the predictions. The ν_μ-like and ν_e-like ND data samples are used to correct the a-priori simulated predictions of FD signal and backgrounds.

The far detector is subjected to a large cosmic background. A combination of CNN and BDT methods are used to reduce this background. The $\nu_e/\bar{\nu}_e$ events (ND and FD) are binned into low and high purity bins for enhanced sensitivity to oscillation fits. A special "peripheral" selection is also included, consisting of events that pass the strict selections by the BDT/CNN exclusively to enhance the selection efficiency. The ν_μ-like and the ν_e-like events distributions at the far detector are shown in Fig. 4.

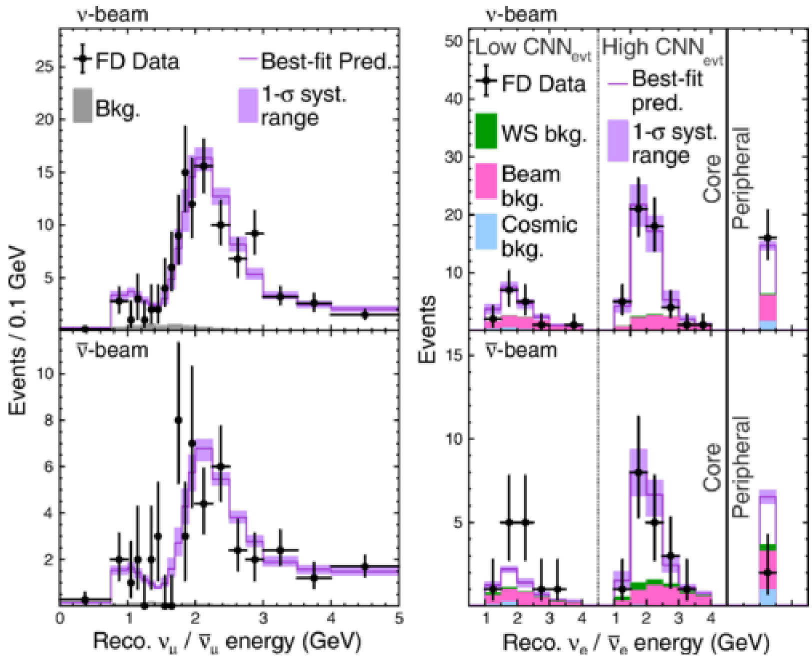

Figure 4: Reconstructed neutrino energy spectra for the FD samples with the neutrino-mode beam and antineutrino-mode for ν_μ-like (left) and ν_e-like (right) events [9].

3.2 Oscillation Results

Oscillation results are obtained post fitting the FD data and including constraints from the ND. Values of the $\delta_{\rm CP}$ in the vicinity of $\delta_{\rm CP} = \pi/2$ are excluded by $> 3\sigma$ for the inverted mass ordering, and values around $\delta_{\rm CP} = 3\pi/2$ in the normal ordering are disfavored at 2σ CL, as can be seen in Fig. 5.

NOvA also made a measurement of $\sin^2 2\theta_{13} = 0.87^{+0.16}_{-0.020}$. The preferred value slightly changes for different ordering and octant combinations. The NOvA analysis also results in favoring the normal ordering of neutrino mass hierarchy and shows a preference for the upper octant of θ_{23}. More details on the oscillation results can be found in Ref. [9].

4. The T2K and NOvA Combined Analysis Status:

A comparison of the T2K $\delta_{\rm CP}$-$\sin^2\theta_{23}$ constraint to those of Super-K [10] and NOvA [11] is shown in Fig. 6. The latest oscillation results from the T2K and NOvA experiments are shown in Fig. 7.

T2K's best-fit value of $\delta_{\rm CP}$ is very consistent with that of Super-K but lies outside of NOvA's 90% CL contours. Both T2K and NOvA prefer the upper octant of θ_{23}, but their

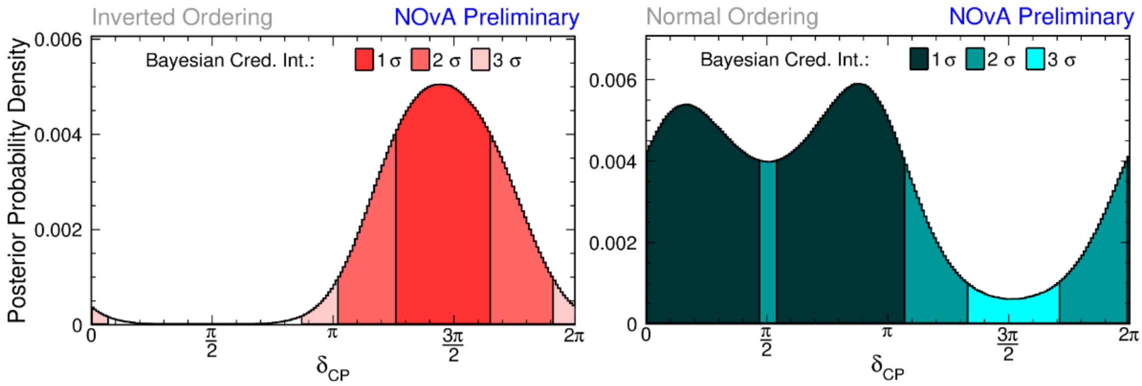

Figure 5: Posterior probability distribution of the δ_{CP} [7]: the inverted mass ordering with $\delta_{CP} = \pi/2$ is excluded at more than 3σ and the normal mass ordering with $\delta_{CP} = 3\pi/2$ is disfavored at 2σ confidence.

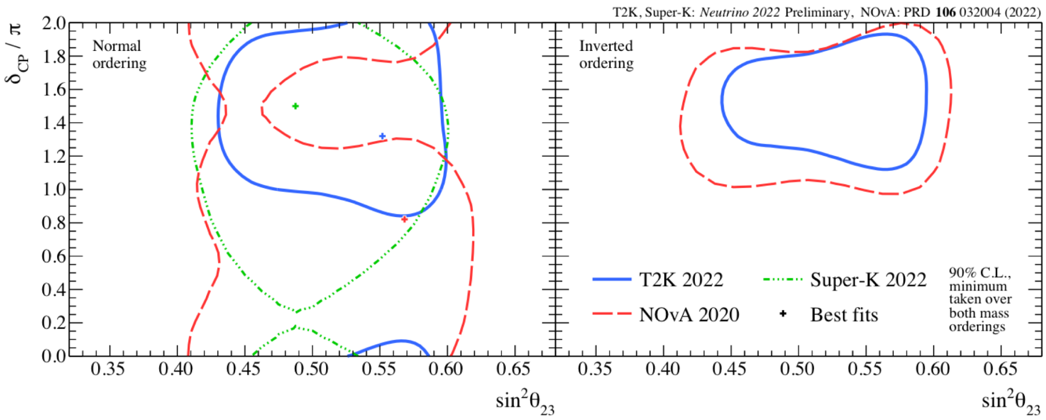

Figure 6: Comparison of the oscillation results from T2K, Super-K and NOvA experiments.

best-fit points, although very close, are just outside of each other's 90% CL contours. There is however an overlap at the 90% CL across both mass orderings.

Hence, a joint fit of the two experiments could potentially aid in convergence towards a solution by exploiting the more vacuum-like measurements at T2K and the stronger matter effects that influence the ordering of the mass hierarchy at NOvA. The two LBL experiments with different baselines, energy ranges, and detector technologies can complement each other to study the oscillations. The two collaborations are currently working on a joint analysis of their data toward ensuring increased sensitivity and ability to break the degeneracy between the mass ordering and δ_{CP} predictions. The combined analysis is almost done and the results will be soon presented to the physics community.

5. Conclusion

The latest neutrino oscillation results from the T2K experiment are presented, which include several improvements in the oscillation analysis owing to improved flux tuning with

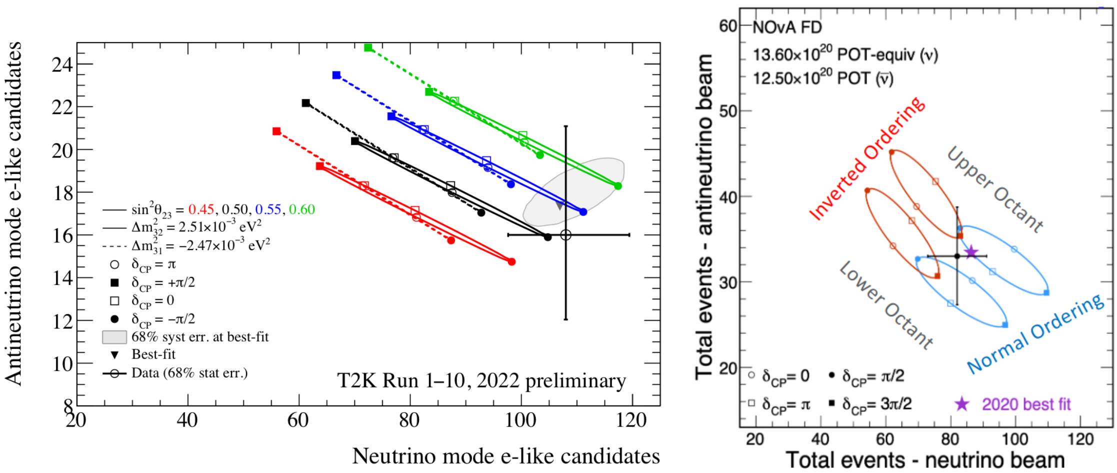

Figure 7: Best-fit points obtained as in the latest results of oscillation analyses by the T2K (left) and NOvA (right) experiments.

the T2K replica target, improved cross-section model constrained with the ND280 data, and new ND280 (and Super-K) event samples. A slight preference is observed for the non-maximal mixing, preferring the upper octant for θ_{23}. The normal ordering of the mass hierarchy is also slightly preferred. The CP conserving values are excluded at 90% C.L.

The latest results from the NOvA Experiment are also presented. A combined analysis of the data from the two experiments is expected to resolve the degeneracy observed in the results. The two collaborations have thus been working on a joint-analysis of their data. The results are almost ready, and will be presented to the physics community very soon. In the mean time, a T2K-SuperK joint-analysis has also been done to improve the δ_{CP} sensitivity.

Apart from the neutrino oscillation studies, a number of cross-section measurements are also going on at both T2K and NOvA. Currently, T2K has started taking data with higher beam power, and more efficient detector systems, recently installed, known as the "ND280-upgrade". These are parts of the upgrades as planned, to ensure measurements of oscillation parameters with more precision in the future, with the next-generation neutrino experiments.

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