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Results and perspectives from T2K on CPV in the neutrino sector

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Summary. — In the T2K long-baseline neutrino oscilliaton experiment, the J-PARC facility is able to produce a high-intensity muon neutrino (antineutrino) beam, which is sent towards the near detector stations (0.28 km) and the far detector Super-Kamiokande (295 km). The change in the measured intensity and the composition of the beam are used to provide information about the oscillation parameters. A simultaneous analysis of the above neutrino and antineutrino mode data sets leads to the first ever sensitivity to the neutrino-sector CPV based on T2K data alone. Also, it gives the most precise T2K measurements of other neutrino oscillation parameters. The proposal of an extension of the currently approved T2K running from 7.8×10^{21} protons on target to 20×10^{21} protons on target and aiming at the initial observation of CPV with 3σ or higher significance assuming maximum CP violation, is also presented.

1. – Introduction

Over the past two decades the investigation of the neutrino properties has delivered many interesting results. In 1998 Super-Kamiokande, as the first experiment, measured oscillations of neutrinos generated in the Earth's atmosphere [1]. Next, the oscillations of the neutrinos coming from the Sun were measured by the SNO experiment in 2001 [2]. The discovery of neutrino oscillations revealed that the neutrinos have a finite mass, so we expect that the weak eigenstates are different from the mass eigenstates, in analogy to the quark system. Both of these discoveries were awarded the Nobel Prize in Physics in 2015. The neutrino mixing is described by a 3×3 unitary matrix, called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [3]. Oscillation probabilities depend on three mixing angles (θ_{13}, θ_{12}, θ_{23}), two independent mass splittings ($|\Delta m^2|$) and one complex CP phase (δ_{CP}) which should be determined experimentally. In the last few years the major advancement in this subject is that the T2K experiment [4] and reactor experiments [5-7]

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have established that all three neutrino mass states are mixtures of all three flavour states, which allows the possibility of *CP* violation in neutrino oscillations. Despite the fact that the values of the three mixing angles and two mass splittings are now known, they need to be determined with a better precision. The θ_{23} angle has the largest measurement uncertainty of all mixing angles and is consistent with maximal mixing ($\theta_{23} = \pi/4$) within the current experimental uncertainties [8]. The observation of ν_μ disappearance is used to measure Δm^2_{32} and θ_{23}. A precise knowledge of θ_{23} is an important input for the future generation of ν_e and $\bar{\nu}_e$ appearance measurements that may answer the questions of what is the mass hierarchy, if $\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$ and whether the neutrinos violate *CP* symmetry.

2. – T2K experiment

T2K is a long-baseline neutrino experiment designed to measure neutrino oscillations parameters. The main goal of T2K is to study and compare ν_μ to ν_e and $\bar{\nu}_\mu$ to $\bar{\nu}_e$ transitions in order to measure θ_{13} and explore δ_{CP}, related to *CP* violation in the lepton sector. T2K is also designed for precision measurement of ν_μ and $\bar{\nu}_\mu$ disappearance to explore θ_{23} ($\bar{\theta}_{23}$) and Δm^2_{23} ($\Delta \bar{m}^2_{23}$) parameters, *i.e.* to test the CPT theorem or new non-standard ν interactions with matter. The cross section measurements in the near detectors are additional purposes of the T2K experiment.

The T2K experiment [9] is located in Japan. A high-intensity beam of muon neutrinos (muon antineutrinos) produced at the J-PARC accelerator complex is sent towards the near detector facility (the ND280 and INGRID detectors, located 280 m away from the neutrino source) and the far detector, Super-Kamiokande (295 km away). The change in the measured intensity and the composition of the neutrino beam between the near and far detectors are used to provide information on the oscillation parameters. The beam is produced by the conventional method. The protons accelerated to 30 GeV hit a graphite target, producing hadrons including pions and kaons. Charged hadrons are then focused by a set of three electromagnetic horns and sent to a decay tunnel where the pions and kaons decay in flight, producing neutrinos (or antineutrinos by the reversing current in magnetic horns). T2K was the first long-baseline experiment using the off-axis beam technique: the far detector, similarly to the near ND280 detector, is located at a 2.5 degrees angle with respect to the beam axis. Despite some reduction in the integrated neutrino flux passing through the far detector, a big advantage is a kinematic focusing of the off-axis beam around the energy corresponding to the maximum of the oscillation probability, which is about 600 MeV. The use of an off-axis neutrino beam also reduces the background for ν_e appearance in the far detector by reducing the high-energy tail which has a relatively large intrinsic ν_e component. Finally, the dominant interaction mode at these energies is the charged current quasi-elastic (CCQE) mode, which allows for the reconstruction of the neutrino energy at the near and far detectors. Additional significant processes are: CCQE-like multi-nucleon interaction, charged current single pion production (CCπ), neutral current single pion production (NCπ). For a precise measurement of the oscillation parameters, T2K is equipped with two near detectors [9]: ND280 and INGRID.

2·1. *INGRID on-axis near detector*. – The on-axis detector INGRID [10] is used to monitor the beam rate, its direction and stability. It consists of 16 $1\,\mathrm{m} \times 1\,\mathrm{m} \times 1\,\mathrm{m}$ cubic modules. Each module is a "sandwich" of 11 scintillator layers and 10 iron layers. They are surrounded by four veto planes. The modules are arranged as follows: seven horizontally, seven vertically, and two off-diagonally. Neutrinos are counted in the detector by reconstructing muons from neutrino charged current interactions. The profile and direction of the neutrino beam are obtained by the use of registered charged current interactions in each module.

2˙2. *ND280 off-axis near detector*. – The ND280 is used to constrain flux and cross-section systematics for oscillation analysis: it measures a flux and cross section before the oscillations occur. It consists of several sub-detectors: Pi-Zero Detector (P0D) and Tracker as the inner detectors, both surrounded by the electromagnetic calorimeter (ECAL) and then by the Side Muon Range Detector (SMRD). All detector components, except the SMRD, are placed inside a 0.2 T magnetic field produced by the recycled magnet from the UA1 experiment. The P0D subdetector, placed upstream inside the magnet, is a "sandwich" of scintillator planes, lead and brass plates, and a water target. It is optimized for the measurement of neutral π^0 production. Gamma rays from a π^0 decay are converted to electromagnetic showers in the lead plates, and are measured in the scintillator detectors. Downstream the P0D, the Tracker consists of two Fine Grained Detectors (FGDs) separated by three Time Projection Chambers (TPCs). The TPCs can measure the momenta of charged particles from the curvature of the tracks in the magnetic field. The momentum resolution for muons is better than 10% at 1 GeV. The FGDs consist of scintillator bars. They provide the target material for neutrino interactions and are optimized for detecting the proton recoils. By combining the TPCs and FGDs, the energy spectrum of ν_μ can be precisely measured based on CCQE (Charged Current Quasi-Elastic) neutrino interactions. The ν_μ and ν_e energy spectra are measured by reconstructing the lepton momentum and by separating electrons from muons using $\mathrm{d}E/\mathrm{d}x$. The inner part of the detector is surrounded by an electromagnetic calorimeter (ECAL) which can tag escaping electrons and positrons from π^0 decays. Additionally, the outermost SMRD detector (scintillator slabs installed in the magnet yoke) is used to detect muons escaping the inner volume and to tag cosmic ray muons.

2˙3. *Far detector*. – The far detector, Super-Kamiokande (SK) [11], is a 50 kton water Cherenkov detector located 1000 m underground in the Mozumi Mine in the Japanese Alps. Its inner detector (ID), 22.5 kton of fiducial volume, is viewed by about eleven thousand 20 inch diameter PMTs. The outer detector (OD), which surrounds the ID, is also a water Cherenkov detector. It is used to veto events that enter or exit the inner detector. SK started its operation in 1996. Apart from having its own rich physics programme, SK is also used as the far detector of the T2K experiment. It has an excellent ability to separate ν_e and ν_μ interactions, which is critical to the study of the appearance of electron neutrinos in a muon neutrino beam. It was verified that the probability of the μ/e misidentification is less than 1% [12]. The lack of a magnetic field in the far detector makes it impossible to separate between ν and $\bar{\nu}$. The events are synchronized with the beamline with the use of a dedicated GPS system.

3. – Data sets

The results presented here are based on data sets for both neutrino and antineutrino modes. This corresponds to a neutrino beam exposure of 7.482×10^{20} protons on target (POT) in neutrino mode and 7.471×10^{20} POT in antineutrino mode for the far detector analysis and an exposure of 5.82×10^{20} POT in neutrino mode and 2.84×10^{20} POT in antineutrino mode for the near detector analysis.

4. – Analysis strategy

The analysis strategy is similar to that used to obtained the previous T2K results [4, 13, 14]. To measure the oscillation parameters, the observed number of neutrino interactions at the far detector is compared with the predicted one. The values of the oscillation parameters are then estimated using a maximum likelihood fit. A tuned prediction of the oscillated spectrum at Super-Kamiokande together with the estimated uncertainty is obtained by fitting charged-current interaction samples at ND280. It should be added that in the present analysis, contrary to the previous ones, both the neutrino and antineutrino samples were fitted simoultaneously at the near and far detector. The neutrino and antineutrino fluxes at the near and far detectors and their correlations are predicted by simulating the hadronic interactions in the target and the propagation and decay of the secondary particles. This simulation is tuned to the experimental results of the CERN NA61/SHINE experiment [15]. Neutrino interactions are simulated based on models with constraints from external data using the NEUT neutrino interaction generator [16]. Systematic uncertainties are incorporated in each step: flux prediction, neutrino interactions and cross sections, and the response of the detectors. Systematic uncertainties for the far detector are evaluated using atmospheric neutrino data and cosmic-ray muon events. The systematic parameters in the neutrino flux and interaction models are constraind by a fit to charged-current candidate samples in the off-axis near detector ND280.

4˙1. *Near detector fit.* – In the ND280 analysis the exclusive sub-samples with neutrino interactions in both fine-grained detectors (FGD1, FGD2) are selected, based on track topologies in the Tracker of the ND280 detector, to constrain the cross section components: CCQE (CC0π sub-sample), CC resonant single pion cross-section parameters (CC1π sub-sample) and CC multi pions, dominated by deep inelastic processes (CCother sub-sample) for neutrino mode [13]. Because of lower statistics in the antineutrino mode, the ND280 fits were done only for two sub-samples: CConeTrack and CCmultiTracks to constrain the CCQE and CCnQE (Charged Current non Quasi Elasic) interactions. For each defined sub-sample in the data and Monte Carlo, the 2d distributions of muon momentum and angle are prepared. Then the fit which varies the parameters related to neutrino energy spectrum and interaction model parameters is performed to obtain the best agreement between the data and simulation. By fitting MC to the near detector data, new flux and neutrino interactions parameter are obtained. After the parameters adjustments, the agreements turn out to be excellent. The parameters adjusted in the ND280 analysis are applied to the SK analysis. The uncertainties in these parameters are in general smaller than those for the prior values. The measurements done at the near detector significantly improve the experimental ability to predict the neutrino event rates and spectra at the far detector. The uncertainties in the predicted number of events at the far detector decrease from 14–12% to about 6–5%.

4˙2. *Far detector fit.* – The selected 4 samples of CCQE ν_μ, ν_e, $\bar{\nu}_\mu$ and $\bar{\nu}_e$ interaction candidates must have a single identified Cherenkov ring associated to the outgoing lepton. They are required to be fully contained in the fiducial volume and have reconstructed neutrino energy $E_{rec} < 1.25\,\mathrm{GeV}$. T2K observes a total of 135 ν_μ and 32 ν_e event candidates for neutrino mode while in case of no oscillations 521.8 and 6.1 events were expected, respectively. For antineutrino mode 66 $\bar{\nu}_\mu$ and 4 $\bar{\nu}_e$ event candidates are selected while in case of no oscillations 184.8 and 2.3 events were expected, respectively.

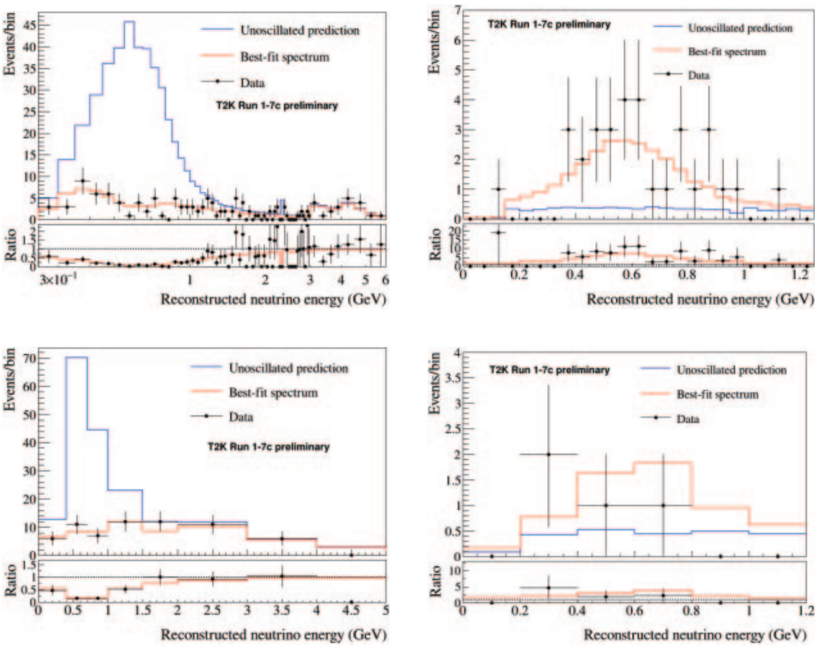

Fig. 1. – Best-fit reconstructed energy spectrum (without reactor constraint on θ_{13}) compared to data and unoscillated spectrum for: ν_μ disappearance (top-left), ν_e appearance (top-right), $\bar{\nu}_\mu$ disappearance (bottom-left) and $\bar{\nu}_e$ appearance (bottom-right).

The reconstructed neutrino energy distribution, the best-fit energy spectrum, the expectation in absence of oscillation, as well as (below each plot) their ratios are presented in fig. 1 for all four SK data samples.

5. – Joint ν and $\bar{\nu}$ oscillation analysis

The values of four oscillation parameters: Δm^2_{32}, θ_{23}, θ_{13} and δ_{cp} are obtained by performing a joint maximum-likelihood fit of the four far detector data samples. In the calculation of the oscillation probabilities the full three flavour oscillation formulae are used [17]. The priors for the solar neutrino oscillation parameters (whose impact is negligible) are the following: $\Delta m^2_{12} = (7.53 \pm 0.18) \times 10^{-5}\,\mathrm{eV}^2/c^4$, $\sin^2 2\theta_{12} = 0.846 \pm 0.021$ and for reactor measurements $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ [8]. Flat priors are used for Δm^2_{32}, θ_{23} and δ_{CP}. The fitting procedure used in this analysis is described in detail in [14,18]. A series of fits is performed where either one or two oscillation parameters are determined and the others are marginalised. The constant $-2\Delta \ln L$ method is applied to set confidence regions, where $-2\Delta \ln L = -2\ln[L(o)/L_{max}]$ is defined as a ratio between the marginal likelihood at the point "o" of the relevant oscillation parameter space and the maximum marginal likelihood.

Three different analyses were performed using different far detector event observable quantities and different statistical approaches. Results from the three methods are in good agreement. The results shown in this paper use a hybrid Bayesian-frequentist approach. This analysis uses the reconstructed lepton energy and angle with respect to the neutrino beam direction of the ν_e and $\bar{\nu}_e$ candidate samples and the neutrino energy reconstructed assuming the CCQE hypothesis for the ν_μ and $\bar{\nu}_\mu$ samples.

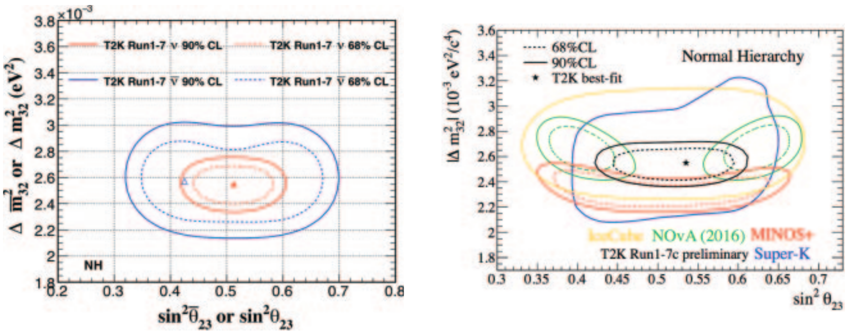

Fig. 2. – Allowed regions in Δm^2_{32} *vs.* $\sin^2 2\theta_{23}$ from the joint analysis for ν_μ (red) and $\bar{\nu}_\mu$ (blue) (left) (T2K preliminary) and comparison to other measurements (right): NOvA [19], MINOS+ [20], SK [21] and IceCube [22].

6. – Investigation of CPV in the neutrino sector

The confidence regions in the $\sin^2 2\theta_{23}$-$|\Delta m^2_{32}|$ plane (fig. 2 (left)) were computed using a reactor measurement of $\sin^2 2\theta_{13}$. The obtained best-fit values are: $\sin^2 2\theta_{23} = 0.532$, $|\Delta m^2_{32}| = 2.545 \times 10^{-3}\,\mathrm{eV}^2/c^4$ ($\sin^2 2\theta_{23} = 0.534$, $|\Delta m^2_{32}| = 2.510 \times 10^{-3}\,\mathrm{eV}^2/c^4$) for normal (inverted) mass hierarchies. This result is consistent with maximal disappearance as in the past analysis results. The T2K data presented here weakly indicate the second octant, *i.e.* $\sin^2 2\theta_{23} > 0.5$ with a posterior probability of 61%. Furthermore, we observe an agreement between the ν_μ and $\bar{\nu}_\mu$ data, so CPT is conserved. In fig. 2 (right) the T2K results are compared with other experiments. This analysis provides world-leading constraints on parameters $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$ which are very important for further CPV analysis.

The confidence regions in the $\sin^2 2\theta_{13}$-δ_{CP} plane are computed independently for both normal and inverted mass hierarchies without using the reactor measurements (fig. 3 (left)). In the analysis, the addition of the $\bar{\nu}$ samples at the far detector gives the first sensitivity to δ_{CP} from the T2K data alone. A good agreement between the T2K results and reactor measurements (yellow band) for $\sin^2 2\theta_{13}$ is observed. The T2K-only data disfavor the region of δ_{CP} close to $+\pi/2$ with a preference for δ_{CP} close to $-\pi/2$, both for normal and inverted hierarchies.

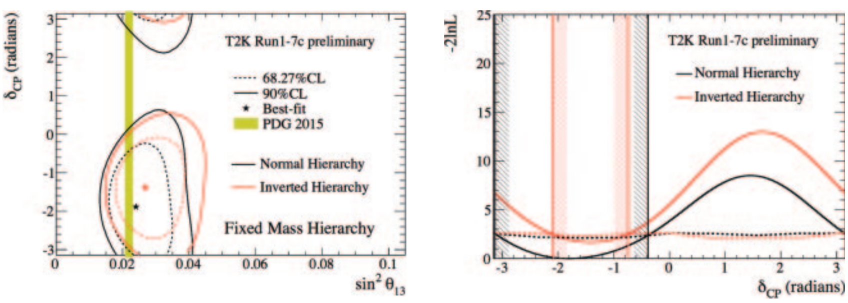

Fig. 3. – 90% confidence regions in δ_{CP} *vs.* $\sin^2 2\theta_{13}$ from the joint analysis without θ_{13} constrained by reactor measurements, yellow band (left) and 90% C.L. intervals in δ_{CP} (right).

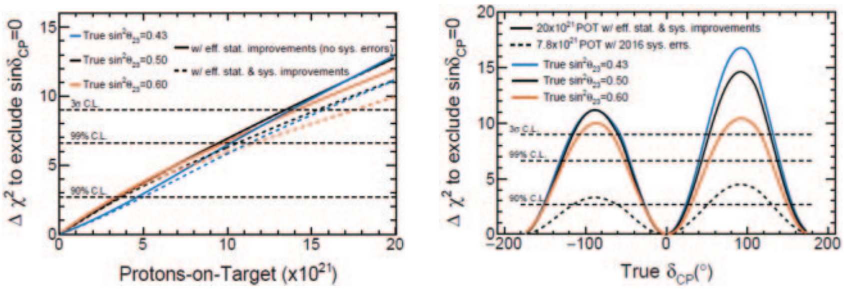

Fig. 4. – Sensitivity to CPV as a function of POT (left) and true δ_{CP} (right) for the full T2K-II exposure of 20×10^{21} with a 50% improvement in the effective statistics. The improved systematic error is applied [24].

Figure 3 (right) shows the confidence interval for δ_{CP} obtained with the Feldman-Cousins method [23], in which the θ_{13} parameter is marginalised using the reactor measurement. The best-fit value is obtained for the normal hierarchy and $\delta_{CP} = -1.791$ near the maximal *CP* volation. For the inverted hierarchy the best-fit value is $\delta_{CP} = -1.414$. The hypothesis of *CP* conservation, *i.e.* $\delta_{CP} = 0$, π, is excluded at 90%. The δ_{CP} confidence intervals at 90% C.L. are $(-3.13, -0.39)$ for normal hierarchy and $(-2.09, -0.74)$ for inverted hierarchy. The normal hierarchy is weakly favored over the inverted hierarchy with a posterior probability of 75%.

7. – Perspectives

The recent experimental T2K results presented here suggest that CPV in neutrino mixing may be determined in the future by long-baseline neutrino oscillation experiments.

There are long-term plans for T2K. We propose an extension of the currently approved T2K running from 7.8×10^{21} protons on target by 2021 (Phase I) to 20×10^{21} protons on target by 2026 (Phase II) [24]. The first stage of this program is to upgrade the accelerator beamline, *i.e.* to improve the J-PARC Main Ring power supplies and to reduce the machine cycles from 2.48 s to 1.3 s, allowing the beam power to rise from 420 kW to about 800 kW. The next stage of upgrading the accelerator and secondary beamline will allow to reach 1300 kW. Also, other improvements, such as increasing the current in the magnetic horns from 250 kA to 320 kA and the optimization of the far detector fiducial volume may increase the effective statistics by up to 50%. Upgrading the near detector ND280 is also planned, which allows to lower systematics. In fig. 4 (left), the expected significance of excluding *CP* conservation as a function of delivered POT for three different values of $\sin^2 2\theta_{23}$ and a true value of $\delta_{CP} = -\pi/2$ was shown. Assuming that mass hierarchy is known from other experiments, we may exclude CP conservation at more than 3σ for any value of $\sin^2 2\theta_{23}$, if δ_{CP} is close to $-\pi/2$, *i.e.* the value currently favored (fig. 4 (right)). This program also contains a measurement of mixing parameters, θ_{23} and Δm^2_{32}, with a precision of at least 1.7 deg and 1%, respectively.

8. – Conclusions

In these proceedings we have presented the first T2K search for *CP* violation in neutrino oscillations using both appearance and disappearance channels in neutrino and antineutrino modes, performed by the T2K experiment alone. The δ_{CP} confidence interval at 90% C.L. is $(-3.13, -0.39)$ for normal hierarchy. The *CP*-conserving values of δ_{CP} (*i.e.*, $\delta_{CP} = 0, \pi$) are excluded at 90% C.L. Futhermore, this analysis also gives very precise measurements of the oscillation parameters $\sin^2 2\theta_{23}$ and Δm^2_{32}. The final results of CPV in the lepton sector, measured by T2K, depend on increasing data statistics used in the analysis and on lowering the systematics. T2K prepared a proposal to extend the data running till 2026 to collect 20×10^{21} POT, aiming at the initial observation of *CP* violation with 3σ or higher significance in the case of maximal *CP* violation with $\delta_{CP} = -\pi/2$.

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