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Search of neutrino CPV with the T2K experiment

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Summary. — In the T2K (Tokai-to-Kamioka) experiment, an off-axis neutrino beam with a peak energy of $\sim$ 0.6 GeV is produced at the J-PARC accelerator facility, with the flavour content dominated by either muon neutrinos or muon anti-neutrinos, depending on the choice of the polarity of the magnetic focusing horns. The neutrino beam is detected first in the near detector ND280, where the flavour composition of the incoming neutrino flux is not expected to be affected by oscillation, and then travels 295 km to the far detector Super-Kamiokande, where oscillation significantly affects the flavour composition. We report the results of a joint analysis of neutrino and anti-neutrino oscillations at T2K, obtained by collecting a total statistic of 2.25×10^{21} protons-on-target (POT). Currently T2K can claim the world leading sensitivity to the neutrino-sector CPV, thanks to a number of critical improvements in the oscillation analysis combined together with a stable operation at intense beam power. In fact, T2K is the first experiment able to reject the CP-conserving values of δ_{CP} at 2σ C.L.

1. – Introduction to neutrino oscillations

Neutrinos are one of the most abundant and elusive elementary particles which make up the universe. They are electrically neutral and interact weakly with the matter, thus it is extremely hard to detect them and study their properties. In 1998 Super-Kamiokande first claimed oscillations of neutrinos generated in the Earth's atmosphere [1]. After few years, in 2001, the oscillations of the neutrinos coming from the Sun were claimed by the SNO experiment [2]. Both of these discoveries were awarded with the Nobel Prize in Physics in 2015. The neutrino oscillations phenomenon, whereby existing neutrinos can transform into each other periodically in time, during their propagation, revealed that the neutrinos have a finite mass. In fact, if neutrinos have a finite mass, the weak

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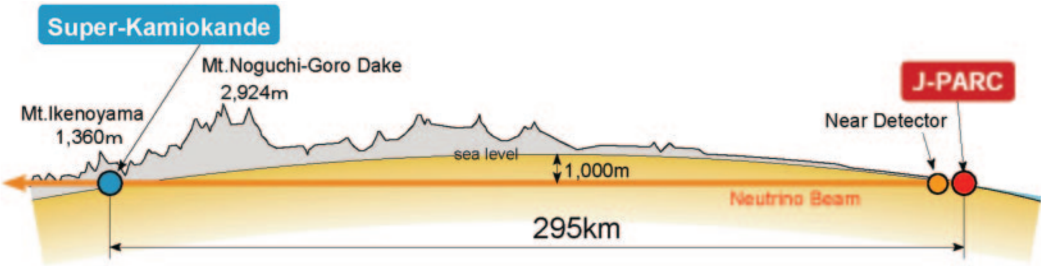

Fig. 1. – Schematic view of the T2K experimental setup.

eigenstate (ν_α) can be parametrised as a linear combination of mass eigenstates (ν_i), according to $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$. $U^*_{\alpha i}$ is a 3×3 unitary matrix, called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [3], in analogy to the Cabibbo-Kobayashi-Maskawa (CKM) matrix in the quark system [4]. The PMNS matrix is parametrised by three mixing angles, θ_{12}, θ_{23}, θ_{13}, and a CP-violating phase, δ_{CP}(1). The additional parameters governing neutrino oscillations are the squared mass differences $\Delta m^2_{ij} = m^2_j - m^2_i$, where m_i is the i-th neutrino mass eigenstate. In more than fifty years, since its first experimental observation, the oscillation parameters, including three mixing angles and two mass-squared differences, were measured with high precision (within 5% uncertainty) by various neutrino oscillation experiments. The current knowledge we have on the oscillation parameters is $\Delta m^2_{21} \approx 7.5 \times 10^{-5}$ eV^2, $|\Delta m^2_{31}| \approx 2.4 \times 10^{-3}$ eV^2 $\theta_{12} \approx 33°$, $\theta_{23} \approx 45°$, $\theta_{13} \approx 9°$. Since the value of θ_{13} has now been precisely measured from reactor experiments Daya Bay [5], RENO [6] and T2K [7], a new era of precision measurements of neutrino oscillations has begun, with the possibility to investigate sub-leading–order effects in order to measure the mass ordering(2) and δ_{CP} in the leptonic sector. Such measurement is today the main goal of the T2K experiment.

2. – The T2K experiment

The Tokai-to-Kamioka (T2K) experiment [8] uses a 30 GeV proton beam from the J-PARC accelerator facility in Tokai (Ibaraki prefecture, Japan), to produce a high-purity muon neutrino beam, which is detected first at 280 m from the neutrino production point in the near detector complex (composed by ND280 and INGRID [9] detectors), where the flavour composition of the incoming neutrino flux is not expected to be affected by oscillations, and then travels 295 km to the far detector Super-Kamiokande [8] (Gifu prefecture, Japan), where oscillations significantly affect the flavour composition. A schematic view of the T2K experimental setup is shown in fig. 1. The near detector ND280 and the far detector Super-Kamiokande (SK) are placed 2.5° off-axis with respect to the neutrino beam centre, resulting in a quasi-monochromatic neutrino energy spectrum that is sharply peaked around 0.6 GeV in order to enhance the effect of neutrino oscillations

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(1) If neutrino is Majorana particle, two additional phases are included but should not take any impact on neutrino oscillation measurements.

(2) Since one of the signs of the squared-mass difference is unknown, there are two ways of ordering the mass eigenstates: normal or inverted. The former refers to the third mass eigenstate being the heaviest, while the latter to the third mass eigenstate being the lightest.

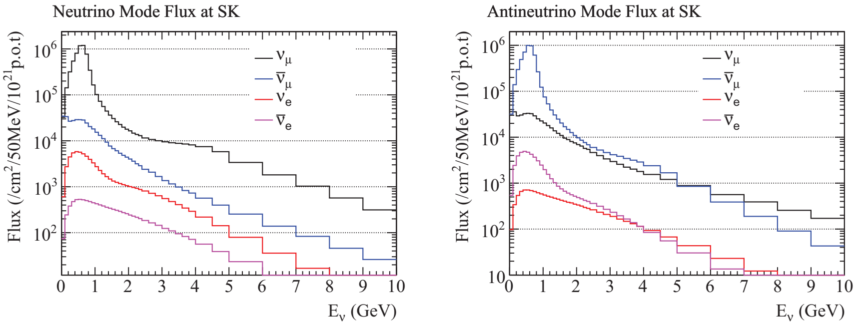

Fig. 2. – Predicted flux of neutrinos and anti-neutrinos by species at the SK detector in the absence of oscillation effects for ν-mode (left) and $\bar{\nu}$-mode (right).

at 295 km, enhance the Charged-Current Quasi-Elastic (CCQE) neutrino (anti-neutrino) interactions(3) and reduce as much as possible the background coming from π^0 interactions that can mimic a ν_e signal. The neutrino flux is obtained by hitting accelerated protons on a 90 cm long graphite target. A set of three pulsed electromagnets ("horn") focuses either positive pions into a helium-filled decay region to produce a beam primarily composed of ν_μ (ν-mode), or negative pions to produce a $\bar{\nu}_\mu$ ($\bar{\nu}$-mode) enhanced beam. The predicted neutrino fluxes in both ν and $\bar{\nu}$ modes at SK are shown in fig. 2. Thus, T2K can investigate two neutrino oscillations channels and two anti-neutrino oscillations channels: ν_μ ($\bar{\nu}_\mu$) disappearance and ν_e ($\bar{\nu}_e$) appearance. In the disappearance channel, the survival probability $P(\nu_\mu \rightarrow \nu_\mu)$, is sensitive to $2\theta_{23}$ and Δm^2_{32}. In the appearance channel, the oscillation probability $P(\nu_\mu \rightarrow \nu_e)$ is sensitive to θ_{13} and the octant of θ_{23} in the leading term, and is sensitive to $\sin\delta_{CP}$ and matter effect in the sub-leading terms. At T2K, the CP-violating phase δ_{CP} has an effect up to $\sim 30\%$, while the matter effect has a lower impact ($\sim 10\%$). This will result in asymmetries in the probabilities for the CP-conjugate channels $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ if $\sin\delta_{CP} \neq 0$ or $\pm\pi$, with negative (positive) values of $\sin\delta_{CP}$ enhancing (suppressing) $\nu_\mu \rightarrow \nu_e$ oscillations and suppressing (enhancing) $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.

2˙1. *ND280 off-axis near detector*. – The T2K off-axis near detector ND280 measures the neutrino energy spectrum, flavour content, and interaction rates of the neutrino beam before the oscillations occur. These measurements are crucial to reduce the uncertainties on neutrino flux and interaction models which affect the prediction on the number of expected events at the far detector. The ND280 detector consists of a set of subdetectors installed inside the refurbished UA1/NOMAD magnet, which provides a 0.2 T field, used to measure the charge and the momentum of particles passing through ND280. Inside the UA1 magnet there are: the π^0 detector (P0D) and the TPC/FGD sandwich (tracker), both of which are surrounded by an electromagnetic calorimeter. Moreover, the UA1 magnet yoke is instrumented with a plastic scintillator to perform as a muon range detector (SMRD). The samples used in the near detector analysis, ν_μ and $\bar{\nu}_\mu$ Charged-Current (CC) interactions are selected in the tracker region of ND280, which consists of three Time Projection Chambers (TPC1, 2, 3) [10], interleaved with two Fine-Grained

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(3) A CCQE interaction ($\nu_l + n \rightarrow l^- + p$, $\bar{\nu}_l + n \rightarrow l^+ + n$) is the main signal at Super-Kamiokande.

Detectors (FGD1, 2) [11]. The upstream FGD1 detector is made of fifteen polystyrene scintillator modules, while the downstream FGD2 contains seven polystyrene scintillator modules interleaved with six water modules. The FGDs provide a target mass for neutrino interactions and track the charged particles coming from the interaction vertex, while the TPCs provide 3D tracking and determine the momentum and energy loss of each charged particle traversing them. The observed energy loss in the TPCs, combined with the measurement of the momentum, is used for particle identification of the charged tracks produced in neutrino interactions in order to measure exclusive CC event rates. Moreover, the combination of the observed energy loss in the tracker with the particle charge information, allows a precise separation and measurement of the $\bar{\nu}_\mu$ (right-sign) and ν_μ (wrong-sign, $\sim 30\%$ at T2K energy peak) when the experiment runs in $\bar{\nu}$-mode.

2·2. *Super-Kamiokande off-axis far detector.* – Super-Kamiokande (SK) is a 50 kton water Cherenkov detector. 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 μ/e separation (less than 1% misidentification probability) and π^0 identification (in case of two separate electron-like rings), which is critical to the study of the appearance of electron neutrinos in a muon neutrino beam. The lack of a magnetic field in the far detector makes it impossible to separate ν and $\bar{\nu}$ interactions. The events arriving at SK from the J-PARC beam spill are synchronised with a GPS within 150 ns precision.

3. – Analysis strategy

The results presented here are based on a total neutrino beam exposure of 2.25×10^{21} POT, 1.49×10^{21} POT in ν-mode and 0.76×10^{21} POT in $\bar{\nu}$-mode. For the T2K oscillation analyses, the expected event rates and spectra at SK are predicted based on a model of neutrino fluxes and of neutrino cross-section and measurements of neutrino interactions at ND280. More details on the oscillation analyses are given in [12]. The neutrino flux from the T2K beam line is predicted from a data-driven simulation based on GEANT3-based Monte Carlo, incorporating data from the NA61/SHINE experiment [13,14], which has provided critical measurements of the hadron production cross-sections using a thin graphite target and a full replica of the T2K target [15]. In addition, beam monitor data and the beam direction, profile and stability, measured by the on-axis near detector INGRID, are incorporated into the flux prediction and its systematic errors, which are reduced at the level of $\sim 10\%$ [16]. The cross-section model is based on external measurements from different experiments (mostly MiniBooNE and MINERνA [17]). Several improvements have been introduced in the cross-section model for the current oscillation analysis with respect to the previous ones. Processes for pion production are now tuned to recent data to hydrogen and deuterium and included in the simulations. In addition, long-range correlations in nucleus and a model for multi-nucleon scattering (Valencia $2p$-$2h$ model [18]) which can mimic the CCQE-like signal observed in the T2K far detector when the knocked-out protons are below the water Cherenkov's threshold (about 1 GeV), are now included in the simulation. Uncertainties on event rates and spectra of the order of $\sim 15\%$ would be expected in the oscillation analysis without using the ND280 data.

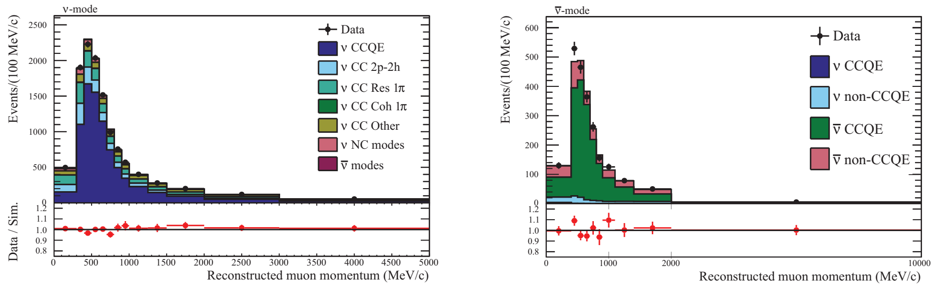

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Fig. 3. – Predicted (histogram) and observed (data point) muon momentum distributions after the near detector fit for ν_μ CC-0π events in ν-mode (left) and $\bar{\nu}_\mu$ CC-1-track events in $\bar{\nu}$-mode (right).

3·1. *Near detector analysis.* – ND280 data are crucial inputs to the T2K oscillation analyses. Neutrino flux and interactions models are fit to the precisely measured, high statistics data at ND280, producing both a better central prediction of the SK event rate and reducing the systematic uncertainties associated with the flux and interaction models. In the ν-mode case, muon neutrino induced CC interactions are selected in both FGDs Fiducial Volumes (FV). The ν_μ CC candidates are divided into three sub-samples, according to the number of identified pions in the event: CC-0π, CC-1π^+ and CC-Other, which are dominated by CCQE, CC resonant pion production, and deep inelastic scattering interactions, respectively. For the $\bar{\nu}$-mode case, both $\bar{\nu}_\mu$ and ν_μ CC interactions are selected and then divided into two sub-samples, defined by the number of reconstructed tracks crossing the TPCs: $\bar{\nu}_\mu$ (ν_μ) CC-1-track, dominated by CCQE interactions and $\bar{\nu}_\mu$ (ν_μ) CC-N-track ($N > 1$), a mixture of resonant production and deep inelastic scattering. The ND280 analysis performs a simultaneous fit of the fourteen samples (seven FGD1 samples and seven FGD2 samples) in muon momentum and polar angle distributions, in order to constrain parameters representing the systematic uncertainties in the neutrino flux and interaction models. The muon momentum distributions of CC-0π sample (ν-mode) and CC-1-track sample ($\bar{\nu}$-mode) in FGD1 after the ND280 fit, are shown in fig. 3. For the parameters that ND280 can constrain, the fit reduces their effect on the uncertainty on the expected number of events at SK from 12–14% to 5–7%.

3·2. *Far detector analysis.* – Another major improvement in this analysis with respect to previous ones is the new reconstruction algorithm used for the Super-Kamiokande event selection. This new algorithm combines simultaneously time and charge likelihood for a given ring hypothesis and it allows an extension of the Fiducial Volume (FV), in which not only the distance of the vertex from the wall but also the direction of the lepton candidate with respect to the wall is used. The new algorithm, combined with the new FV definition, increases by 30% the efficiency in selecting e-like samples while keeping the same purity of ∼80%. For the μ-like sample the new selection allows to increase the purity of charged-current interactions without pions in the final state from 70% to 80%. SK provides five samples in total to the oscillation analysis, 4 CCQE-like samples and one CC1π^+ sample: single-ring μ-like events (1Rμ), both in ν-mode and $\bar{\nu}$-mode, *i.e.*, events with a single Cherenkov ring, required to have a pattern consistent with a muon and a momentum of at least $200\,\mathrm{MeV}/c$; single-ring e-like events (1Re), both in ν-mode and $\bar{\nu}$-mode, *i.e.*, events with a single ring, with a pattern consistent

TABLE I. – *Observed and expected numbers of events at SK for different values of* δ_{CP}.

	Data	MC $\delta_{CP} = -\pi/2$	MC $\delta_{CP} = 0$	MC $\delta_{CP} = +\pi/2$	MC $\delta_{CP} = \pm\pi$
ν-mode 1Re	74	73.5	61.5	49.9	61.5
ν-mode 1R$e + 1\pi^+$	15	6.9	6.0	4.9	5.8
ν-mode 1Rμ	240	267.8	267.4	267.7	268.2
$\bar{\nu}$-mode 1Re	7	7.9	9.0	10.0	8.9
$\bar{\nu}$-mode 1Rμ	68	63.1	62.9	63.1	63.1

with an electron, a visible energy greater than 100 MeV and no decay electrons which may flag the presence of pions in the event; finally the ν_eCC1π^+ sample, selected only in ν-mode, where the e-like ring is accompanied by the presence of a delayed electron, due to the decay of a π^+ produced in the neutrino interaction (1R$e + 1\pi^+$). The number of selected events for each sample are listed in table I and compared with Monte Carlo expectations for different values of δ_{CP}.

In the four CCQE-like samples, the neutrino energy (E_ν) is reconstructed from the momentum and direction of the lepton (assuming the kinematics of a CCQE interaction and neglecting Fermi motion), while in the CC1π^+ sample, E_ν is reconstructed like in the CCQE case, but assuming that in the final state a Δ^{++} baryon is produced instead of a proton. The resulting energy distributions for the five samples are shown in fig. 4.

As can be seen from table I, δ_{CP} only affects the e-like samples and values of δ_{CP} close to $-\pi/2$, make the ν_e ($\bar{\nu}_e$) appearance probability larger (smaller) than for $\delta_{CP} = 0, \pm\pi$. This is what is observed in the data in ν-mode ($\bar{\nu}$-mode), where 74 (7) 1Re events are

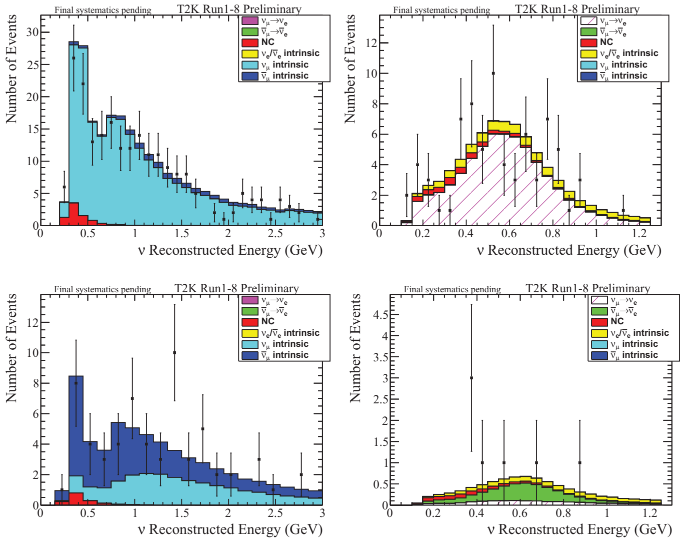

Fig. 4. – Predicted (histogram) and observed (data point) muon momentum distributions after the near detector fit for ν_μ CC-0π events in ν-mode (left) and $\bar{\nu}_\mu$ CC-1-track events in $\bar{\nu}$-mode (right).

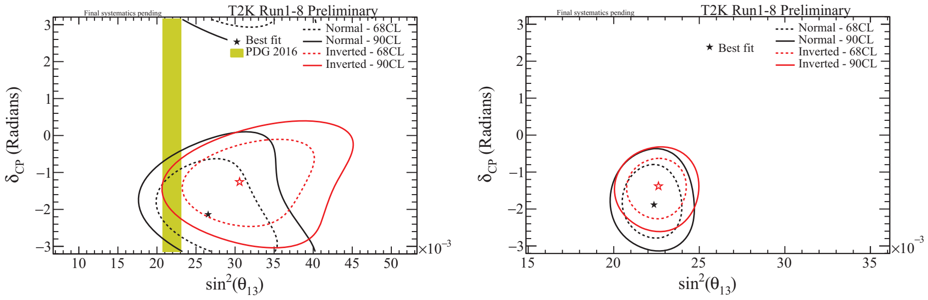

Fig. 5. – Left: T2K oscillation results on δ_{CP} *vs.* $\sin^2\theta_{13}$ without reactor constraint (yellow band). Right: T2K oscillation results on δ_{CP} *vs.* $\sin^2\theta_{13}$ with reactor constraint.

observed while 62 (9) are expected if $\delta_{CP} = 0, \pm\pi$.

4. – Oscillation results

A likelihood-ratio formed with the five samples collected at SK (1Re/1Rμ in $\nu/\bar{\nu}$-mode and 1Re + $1\pi^+$ in ν-mode), it is used as test statistic ($-2\Delta\log\mathcal{L}$) where the nuisance parameters (flux, cross-section, detector and oscillation) are marginalised and the marginal likelihood is maximised as a function of the oscillation parameters of interest: θ_{23}, Δm^2_{32}, θ_{13} and δ_{CP}. The value of θ_{13} can either be a free parameter in the fit or it can be constrained to the precise measurement of the reactor experiments. The two cases are shown in fig. 5 and as can be seen from the plot on the left, the T2K results on θ_{13} are consistent with reactor ones, with the preference on the maximally CP-violated region at $\delta_{CP} = -\pi/2$. The right plot in fig. 6 shows the $-2\Delta\log\mathcal{L}$ as a function of δ_{CP} and mass hierarchy, with the reactor constraint on $\sin^2 2\theta_{13}$ [5, 6]. The 2σ confidence levels are built with the Feldman-Cousins method [19], resulting in the interval [−2.98, −0.60] in normal hierarchy and [−1.53,−1.19] in inverted hierarchy. The T2K measurement rejects CP conservation in neutrino oscillations for both mass hierarchy hypotheses with 2σ confidence level. From a toy Monte Carlo study (fig. 6, right) we find that, if the true value of $\delta_{CP} = -\pi/2$, then the probability for excluding $\delta_{CP} = 0$ or $\pm\pi$, at 2σ confidence level is 30% and 20%, respectively.

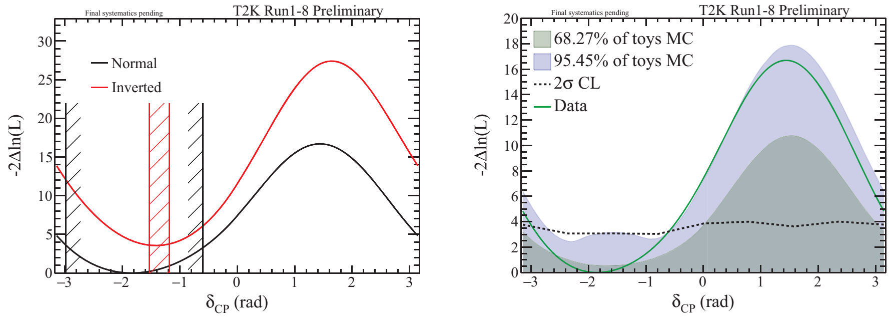

Fig. 6. – Left: 2σ confidence intervals for the measured $-2\Delta\log\mathcal{L}$ distributions. Critical values are obtained with the Feldman-Cousins method. Right: the distribution of $-2\Delta\log\mathcal{L}$ *vs.* δ_{CP} obtained with 10^4 toy experiments generated with $\delta_{CP} = -1.833$ and normal hierarchy.

5. – Conclusions and prospects

We present the results of a joint analysis across all four neutrino oscillation modes observed at T2K ($\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance), obtained with a total neutrino beam exposure of 2.25×10^{21} POT (1.49×10^{21} POT in ν-mode and 0.76×10^{21} POT in $\bar{\nu}$-mode). Thanks to several improvements in the analysis, like the new cross-section model constrained by ND280 data, the new SK reconstruction algorithm and FV, able to increase by $\sim 30\%$ the expected number of e-like events, together with a stable neutrino beam operation, we claim that CP conservation is excluded at 2σ C.L. and our data still favour the scenario of $\delta_{CP} = -\pi/2$ and normal hierarchy. The T2K Collaboration proposes further extension of the T2K run (T2K-II) up to 2026 in order to collect 20×10^{21} POT, nearly three times the current approved 7.8×10^{21} POT. Such extension of T2K is needed in order to measure the CP-violating effects with $\sim 3\sigma$ sensitivity, if the true value of δ_{CP} is $-\pi/2$ and the mass hierarchy is normal, and to solve the octant of θ_{23} with a precision of 1.7°. In order to fully profit of the additional statistics we need to reduce our neutrino cross-section uncertainties with ND280. For this reason, we launched the ND280 upgrade project to increase the near detector phase-space coverage, to bridge the gap from the current acceptance, essentially limited to forward going tracks, and the almost 4π acceptance of the far detector SK. A near detector with a 4π acceptance can be crucial to further decrease our cross-section uncertainty on the number of predicted events at SK.

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