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Recent results from the T2K experiment

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Abstract. Recent results of the analysis of 2.23×10^{21} POT data collected by the T2K long-baseline neutrino accelerator experiment are presented in this paper. It is shown that T2K is able to constrain the CP-violating phase δ_{CP} in the lepton sector with 2σ significance. Nearest plans for improving the sensitivity to δ_{CP} are also given.

1 Introduction: Neutrino Oscillations

Neutrinos of three flavours ($\nu_e; \nu_\mu; \nu_\tau$), which take part in the weak interactions, do not have definite masses, however their flavour fields can be expressed as linear combinations of neutrino fields with definite masses ($\nu_1; \nu_2; \nu_3$). Massive neutrinos can be either Dirac of Majorana, and their mixing is described by an unitary matrix U_{PMNS} (Pontecorvo-Maki-Nakagawa-Sakata) [1].

If neutrinos of a certain flavour are produced at a source (for example at a particle accelerator or nuclear reactor), then at some distance from the source one can detect either a deficit of neutrinos of the same flavour (”disappearance”) or an excess of neutrinos of another flavour (”appearance”). This phenomenon (called ”neutrino oscillations”) can be parametrized by three mixing angles, θ_{12} (historically called as ”solar”), θ_{23} (”atmospheric”), θ_{13} (”reactor”), and one CP-violation phase δ_{CP} (in the *Dirac* case).

Besides these 4 parameters the oscillation *probability* depends on neutrino masses (m_1, m_2, m_3), mass ordering (hierarchy), and *L/E* ratio, where L is the path length of neutrino with energy E. Experiments with $L \sim O(100$ km) are called ”long-baseline”, or *LBL* (in contrast to *SBL*, ”short-baseline”, with $L \sim O(10$-100 m)). Oscillation neutrino experiments (*LBL* and *SBL*) are sensitive not to the absolute neutrino masses, but to the squared mass differences ($\Delta m^2_{ij} \equiv m^2_i - m^2_j, i \neq j$), thus, they can not distinguish *Dirac* or *Majorana* cases. Since by definition $\Delta m^2_{21} + \Delta m^2_{32} + \Delta m^2_{13} = 0$, only two values of Δm^2_{ij} are independent.

Currently, the open questions in understanding of the neutrino oscillations are the following: is there CP-violation in these processes ($\sin\delta_{CP} \neq 0$?); what is the *mass ordering* of neutrinos: *normal* ($m_3 > m_1$) or *inverted* ($m_3 < m_1$); is the mixing angle θ_{23} *maximal* ($\sin^2\theta_{23} \approx 0.51$), and if not, to which *octant* θ_{23} belongs: to the lower ($\theta_{23} < 45°$) or to the upper one ($\theta_{23} > 45°$)?

The following sections describe details and recent results of the T2K experiment, which tries to find answers to some of these questions.

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2 T2K Experiment

T2K (Tokai-to-Kamioka) is an *LBL* experiment, in which muon (anti)neutrinos are produced in Tokai, at J-PARC (Japan Proton Accelerator Research Center) and directed towards Kamioka Observatory situated 295 km away [2].

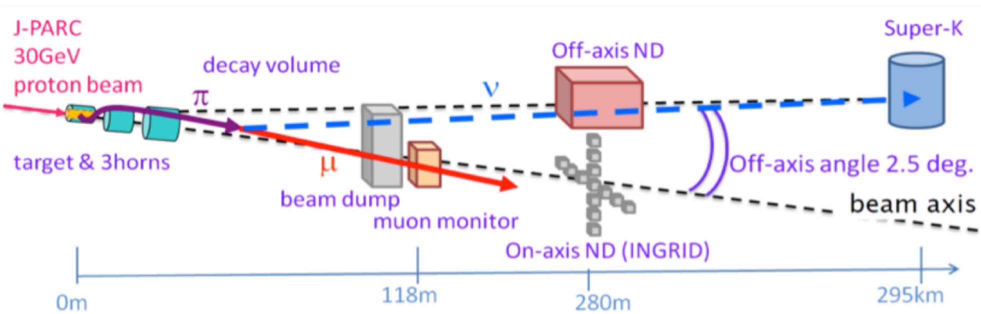

Figure 1. Schematic view of the T2K experiment: 30-GeV protons hit a graphite target (p+$C \to \pi^{\pm}$+X), then $\pi^{\pm}$s decay and produce muon (anti)neutrinos. The near detectors (off-axis ND280 and on-axis INGRID) are situated at 280 m, and the far detector Super-Kamiokande is 295 km away from the target.

The initial goals of T2K were the discovery of $\nu_\mu \to \nu_e$ oscillations (which corresponds to the case $\theta_{13} \neq 0$) and precise measurement of the "atmospheric" parameters ($\theta_{23}, |\Delta m^2_{32}|$). After discovery of nonzero value of the θ_{13} in 2013 the T2K experiment aims to probe the CP-violating phase δ_{CP} in the lepton sector.

As schematically shown in Fig. 1, the muon *neutrino* beam at T2K is obtained as result of decays of positive pions ($\pi^+ \to \mu^+ + \nu_\mu$), which in turn are produced in nuclear reactions of 30-GeV protons in a special graphite target and focused by three magnetic horns. The muon *antineutrino*-enhanced beam is obtained by reversing the horn currents (as result of decays of negative pions $\pi^- \to \mu^- + \bar{\nu}_\mu$).

One of the main features of the T2K experimental setup is an implementation of the so-called *off-axis* beam concept: due to kinematics of the $\pi^{\pm}$ decays at some small angles (with respect to the initial proton beam) the produced neutrinos have an energy spectrum with a rather narrow peak which could be tuned to the oscillation maximum/minimum. In T2K the value of 2.5° off-axis angle is found to be the best for the fixed L/E ratio (L = 295 km and $E \approx$ 600 MeV), it also allows the flux of neutrinos from the high-energy tail to be suppressed, neutral-current interactions of which can mimic the signal events.

T2K has two *near* detectors at 280 meters from the graphite target (INGRID and ND280) and one *far* detector at 295 km (Super-Kamiokande), see Fig. 1.

The *on-axis* INGRID (Interactive Neutrino GRID) detector consists of 14 sandwich modules installed in a shape of a 10 m × 10 m cross, and a fully-active proton module (in 2017 the proton module was replaced by a water module). Each of sandwich modules weighs about 10 t and comprises layers of plastic scintillators and iron plates. The main objectives of the INGRID are the following: measure the beam rate, beam direction and neutrino cross sections.

The former CERN *UA1* magnet not only provides a magnetic field perpendicular to the beam direction, but also serves to support the *off-axis* detector complex ND280 (Fig. 2).

The ND280 consists of the *tracker* with 2 FGDs (fine-grained detectors) and 3 TPCs (time projection chambers), where the momenta and charge of particles are determined in the mag-

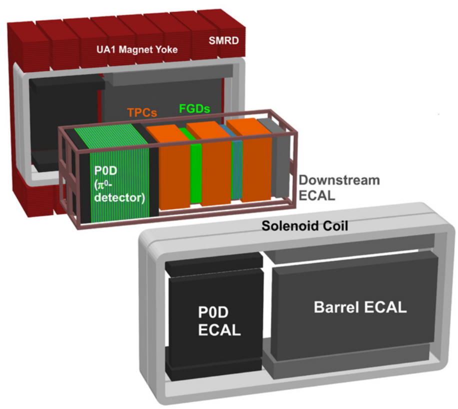

Figure 2. Off-axis ND280 detector complex.

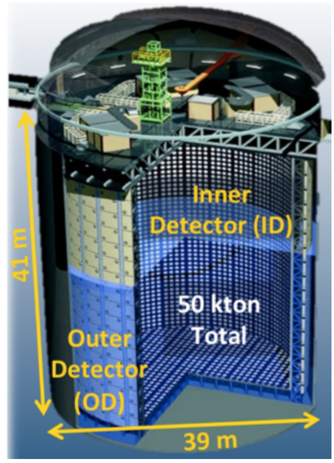

Figure 3. T2K off-axis far detector: Super-Kamiokande.

netic field of 0.2 T; P0D (π^0-detector with a set of neutrino targets); ECAL (electromagnetic calorimeter); SMRD (side muon range detector). One of the FGDs (FGD1) is fully active detector made of plastic scintillators, while the other one (FGD2) contains active plastic and passive water modules. The ND280 detector as a whole measures neutrino beam properties *before* oscillations, constrains the neutrino flux and cross-section parameters used for the *oscillation* analysis.

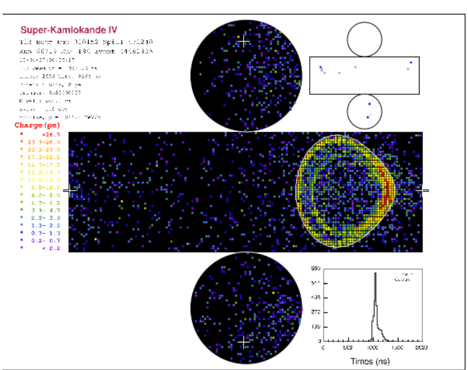

Figure 4. SK event display: ν_μ candidate event (each colour pixel corresponds to a charge collected from one PMT).

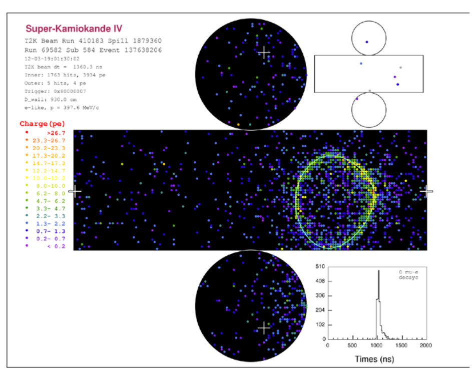

Figure 5. SK event display: ν_e candidate event.

Super-Kamiokande (SK), a 50-kiloton water-Cherenkov detector, serves as the T2K *far* detector situated at 2.5° off-axis angle 295 km away from J-PARC (Fig. 3) in the mine under Mount Ikenoyama (2700 mwe). *SK* comprises two optically isolated detectors: the *inner* (ID) and *outer* (OD). The *ID* contains ~11,000 photoelectron multipliers (PMTs) of 50-cm diameter (40% photo-coverage), the *OD* contains ~2000 PMTs of 20-cm diameter. The *OD* and

Table 1. Observed and expected numbers of T2K SK events (for total 2.23×10^{21} POT)

Data sample	**Data**	MC $\delta_{CP} = -\pi/2$	MC $\delta_{CP} = 0$	MC $\delta_{CP} = \pi/2$	MC $\delta_{CP} = \pi$
ν_μ-like, ν-mode	**240**	267.8	267.4	267.7	268.2
ν_e-like, ν-mode	**74**	73.5	61.5	49.9	62.0
ν_e $CC1\pi$-like, ν-mode	**15**	6.9	6.0	4.9	5.8
$\bar{\nu}_\mu$-like, $\bar{\nu}$-mode	**68**	63.1	62.9	63.1	63.1
$\bar{\nu}_e$-like, $\bar{\nu}$-mode	**7**	7.9	9.0	10.0	8.9

ID utilise the timing and charge information collected from the PMTs which detect photons from the Cherenkov cones of light created by the relativistic charged particles in the pure water of the SK tank (~39 m diameter and ~41 m height). During the T2K beam time the SK detector is synchronized with the J-PARC proton beam by the Global Positioning System (GPS).

The *OD* plays a role of a veto detector suppressing background events from cosmic rays or surrounding rocks, and the *ID* is the main neutrino detector, which demonstrates excellent μ/e separation allowing Cherenkov rings produced by muons (Fig. 4) or electrons (Fig. 5) from neutrino interactions to be distinguished.

T2K started data taking in 2010 in neutrino mode, and since 2014 it alternates running in antineutrino and neutrino modes. The approved goal of T2K is 7.8×10^{21} protons on target (POT). In this paper the results of analysis of 2.23×10^{21} POT (1.47×10^{21} POT in ν- and 0.76×10^{21} POT in $\bar{\nu}$-beam modes) collected by the 12th of April, 2017 are presented[1].

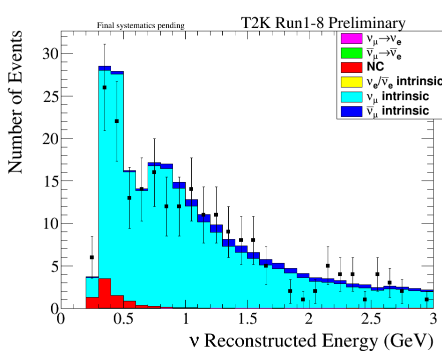

Figure 6. Reconstructed neutrino energy distribution: ν_μ-like events, ν-beam mode (1.47×10^{21} POT.)

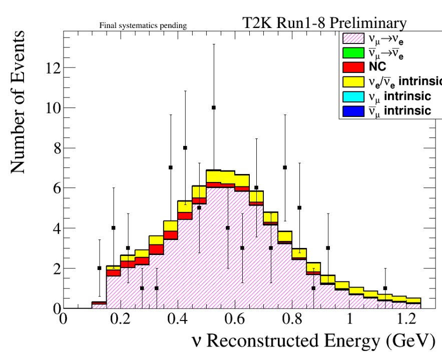

Figure 7. Reconstructed neutrino energy distribution: ν_e-like, ν-beam mode (1.47×10^{21} POT).

3 T2K Analysis and Recent Results

To obtain values of the *oscillation* parameters (θ_{23}, θ_{13}, $|\Delta m^2_{23}|$, δ_{CP}) T2K compares the observed SK data with predictions based on the model parameters (flux, neutrino interaction,

[1]By the end of May 2018 T2K has collected 3.16×10^{21} POT: 1.51×10^{21} POT in ν- and 1.65×10^{21} POT in $\bar{\nu}$-beam modes; the analysis of all T2K data is underway

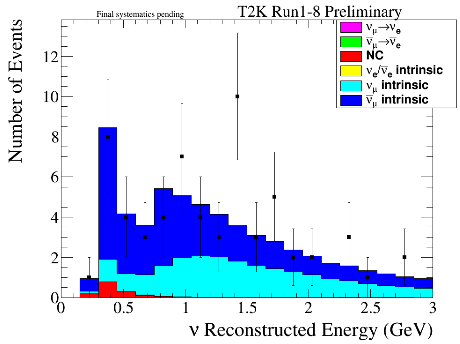

Figure 8. Reconstructed neutrino energy distribution: $\bar{\nu}_\mu$-like events, $\bar{\nu}$-beam mode (0.76×10^{21} POT).

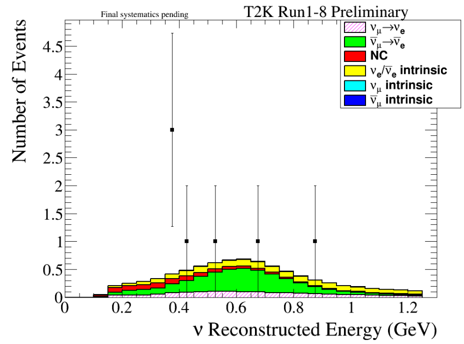

Figure 9. Reconstructed neutrino energy distribution: $\bar{\nu}_e$-like events, $\bar{\nu}$-beam mode (0.76×10^{21} POT).

near/far detector response, systematic) implemented in Monte Carlo simulations. Some of these parameters (flux, cross sections, systematics) are *constrained* by using 14 data samples of the ND280 detector, which allows one to reduce systematic uncertainties of the oscillation parameters. The *oscillation* analysis itself is quite complicated technically, but the idea behind it is rather simple.

After applying special selection criteria (aiming to reject different backgrounds) to the events in the T2K far detector, *five* SK data samples are formed: ν_μ-like (Fig. 6), ν_e-like (Fig. 7), ν_e $CC1\pi$-like (Fig 10) in the ν-beam mode, $\bar{\nu}_\mu$-like (Fig. 8)) and $\bar{\nu}_e$-like (Fig. 9)) in the $\bar{\nu}$-beam mode (Table 1). It should be noted here that the estimated *systematic* uncertainties for the predicted numbers of events lay in the 4–7% range (except for the ν_e $CC1\pi$-like events, where it is around 20%), and the main contributions are related to the cross-section, SK-detector and SK final-state interaction and photonuclear-reaction uncertainties.

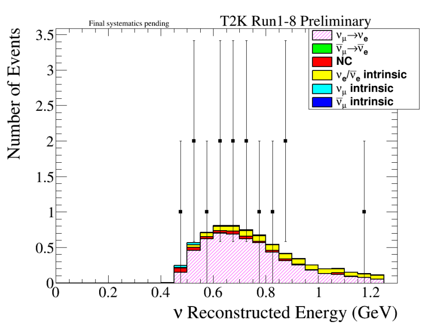

Figure 10. Reconstructed neutrino energy distribution: ν_e $CC1\pi$-like, ν-beam mode (1.47×10^{21} POT).

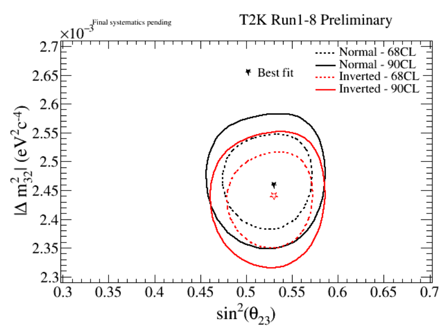

Figure 11. 68%- (dotted) and 90%- (solid) confidence regions for the ($|\Delta m^2_{32}|$, θ_{23}) parameters and best-fit values for *normal* (black) and *inverted* (red) ordering.

All five selected data samples are then *jointly* analyzed. A binned likelihood $L(\hat{\mathbf{o}}, \hat{\mathbf{p}})$ is built for these data samples, where $\hat{\mathbf{o}}$ are the oscillation parameters, and $\hat{\mathbf{p}}$ represents the other parameters. Then $L(\hat{\mathbf{o}}, \hat{\mathbf{p}})$ is *marginalized*, i.e., integrated over $\hat{\mathbf{p}}$ and some of the $\hat{\mathbf{o}}$ parameters, after that the *maximum* of the likelihood L is searched by varying the free $\hat{\mathbf{o}}$ parameters. Then the values of the oscillation parameters are extracted (for details of the analysis methods see [3]).

The best-fit values of $\sin^2\theta_{23}$ are $0.526^{+0.032}_{-0.036}$ for the *normal* and $0.530^{+0.030}_{-0.034}$ for the *inverted* ordering , and that of $|\Delta m^2_{32,13}|$ are $(2.463 \pm 0.065) \times 10^{-3} eV^2/c^4$ for the *normal* and $(2.431^{+0.065}_{-0.064}) \times 10^{-3} eV^2/c^4$ for the *inverted* ordering (Fig. 11). The result is consistent with maximal ν_2 and ν_3 mixing (maximal $\nu_\mu \to \nu_\mu$ disappearance).

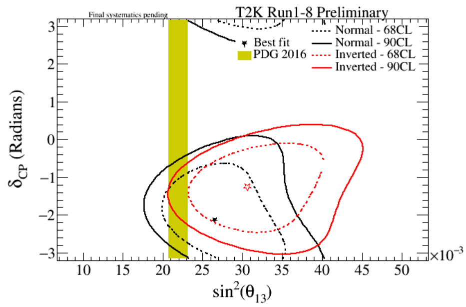

Figure 12. T2K only (*without* reactor constraint): 68%- (dotted) and 90%- (solid) confidence regions for the (δ_{CP}, $\sin^2\theta_{13}$) parameters and best-fit values for *normal* (black) and *inverted* (red) ordering.

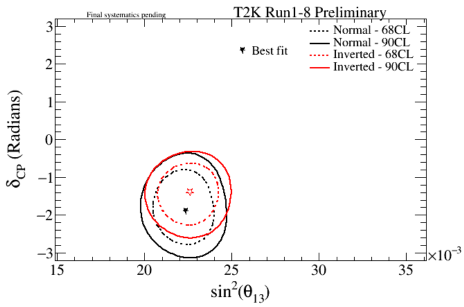

Figure 13. The same as in Fig. 12, but *with* reactor constraint (note the change of the horizontal scale).

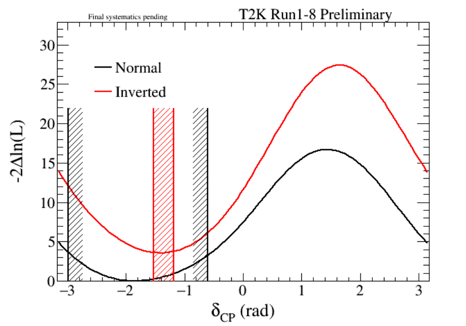

Figure 14. Confidence intervals for the δ_{CP} obtained using the reactor constraint for *normal* (black) and *inverted* (red) mass ordering (vertical lines correspond to allowed 2σ regions).

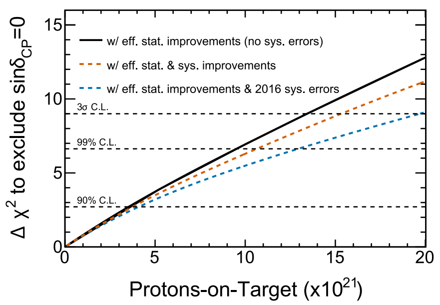

Figure 15. Sensitivity to CP violation of the T2K and T2K-II as a function of POT assuming the true mass ordering is *normal*, but unknown, and the true value of $\delta_{CP} = -\pi/2$ and different assumptions for the systematics (black: no systematic errors; red: improved statistical and systematic errors; blue: with statistical and systematic errors at the level of 2016 analysis) [4].

As seen from Fig. 12, T2K's only result for $\sin^2\theta_{13}$ is compatible with that of the reactor experiments. Using the reactor θ_{13} results T2K is able to constrain the CP-violating phase δ_{CP} (Fig. 13). The T2K confidence intervals obtained for the δ_{CP} are shown in Fig. 14 where the reactor measurement was used as a prior. The vertical lines with hatching (black for *normal*, red for *inverted* ordering) constrain the allowed 2σ regions of δ_{CP}, and it is seen that CP-conserving values $\delta_{CP} = 0$ and $\delta_{CP} = \pi$ are excluded at 95% confidence level. The best-fit value is $\delta_{CP} = -1.87$ for *normal* and $\delta_{CP} = -1.43$ for *inverted* ordering, which is close to maximal *CP* violation.

4 T2K Near Future

As already mentioned, by the end of May 2018 T2K has collected 3.16×10^{21} POT, which corresponds to about 40% of the approved 7.8×10^{21} POT. This goal was approved at the time when the θ_{13} value was assumed to be small. Now it is known that θ_{13} is large, and a new goal of a search for CP violation in the lepton sector has arisen. In order to increase the sensitivity to δ_{CP}, T2K has proposed an extension of the experiment to a new goal of 20×10^{21} POT (T2K-II) [4]. This can help T2K to confirm CP violation with 3σ significance (if δ_{CP} is within the current confidence range), see Fig. 15.

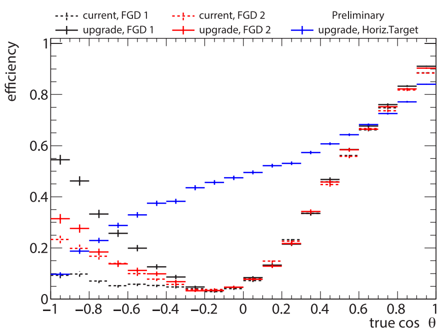

Figure 16. Efficiencies of the FGDs (black and red) and of the proposed sFGD (blue) as a function of the $\cos\theta$, where θ is the lepton angle with respect to the beam.

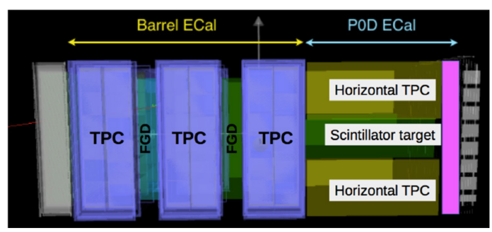

Figure 17. ND280 upgrade (baseline proposal): P0D is replaced by 2 horizontal TPCs and a fully active scintillator neutrino target (ν-beam enters from the right).

In order to achieve this new goal in about 5 years (2021-2026) it is necessary: 1) to reach $\sim$ 1MW power of the J-PARC Main Ring (currently it stably works at about 485 kW); 2) to reduce the main systematics. While the first item is far beyond the scope of this paper, a few words can be added about the second one.

One of the limiting factors that affects the overall systematics is the current ND280 tracker design, which has a poor efficiency for tracks perpendicular to the beam direction (Fig. 16), while the SK detector has a good efficiency for *all* directions of the charged leptons (with momenta above Cherenkov threshold). To improve this situation, a new project, ND280 Upgrade, was launched within T2K in collaboration with the Neutrino Platform at CERN. In the baseline proposal the new ND280 has a fully active neutrino target made of scintillator cubes (Super-FGD, or sFGD, with ~2 million cubes of 1 cm size) and two horizontal TPCs (Fig. 17). This new detector will replace the current P0D [5]. The R&D work on the sFGD and new TPCs started in 2017, and first tests show feasibility of the proposal.

5 Summary

Recent results of the analysis of 2.23×10^{21} POT data collected by the T2K experiment are presented in this paper. It is shown that T2K is able to constrain the CP-violating phase δ_{CP} in the lepton sector with 2σ significance (CP-conserving values $\delta_{CP} = 0$ and $\delta_{CP} = \pi$ are excluded at 95% confidence level). T2K aims to improve the sensitivity to δ_{CP} by increasing the statistics to 20×10^{21} POT (T2K-II), and by upgrading the ND280 detector in order to reduce the systematic uncertainties.

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