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Most recent T2K results on CPV in neutrino sector

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Summary. — The T2K experiment is a long baseline neutrino oscillation experiment located in Japan, using a neutrino beam generated at J-PARC accelerator complex. The beam may be produced in ν_μ or $\bar{\nu}_\mu$ mode. The oscillations are studied by measuring neutrino interactions in near detector complex 280 meters from the beam source and in far detector Super-Kamiokande 295 km away. Particularly interesting aspect of the oscillation analysis is probing the CP violation phase δ_{CP} by comparing ($\nu_\mu \to \nu_e$) and ($\bar{\nu}_\mu \to \bar{\nu}_e$) appearance probabilities. We present results of the joint oscillation analysis for neutrino and anti-neutrino samples based on total collected statistics of 3.13×10^{21} POT. CP conservation is excluded at 2 σ level and Normal Hierarchy is preferred with posterior probability of 89%.

1. – Introduction: neutrino oscillations

One of the most important fronts in the neutrino physics is studying the phenomenon of neutrino oscillations. It is a quantum effect related to the fact that neutrinos interact as flavour eigenstates (ν_e, ν_μ, ν_τ) but propagate as a superposition of three mass eigenstates (ν_1, ν_2, ν_3). As a result a neutrino created in a certain flavour may interact as a different flavour state after propagating over a long distance. The flavour-mass mixing is described by Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [1, 2]:

$$\begin{bmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{bmatrix},$$

where $s_{ij} = \sin(\theta_{ij}), c_{ij} = \cos(\theta_{ij})$, θ_{ij} are three mixing angles (θ_{12}, θ_{13}, θ_{23}) and δ_{CP} is a CP violation phase. Additional parameters are two squared mass differences $\Delta m^2_{ij} = m^2_i - m^2_j$, which don't impact flavour-mass mixing, but appear in oscillation probabilities

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formulas. The sign of Δm^2_{32} remains unknown, leading to two possible mass hierarchies: Normal ($m_3 > m_2 > m_1$, Δm^2_{32} ¿ 0) or Inverted ($m_2 > m_1 > m_3$, Δm^2_{32} ¡ 0).

The oscillations can be studied in two types of measurements. Starting with a pure neutrino beam of a known flavor ν_l one can check how many neutrinos of this flavor have disappeared (disappearance measurement) or look for neutrinos of different flavor $\nu_{l'}$ (appearance measurement). By choosing the ratio L/E of propagation distance (baseline) to neutrino energy the experiment can be sensitive to different values of Δm^2_{ij}.

The values of squared mass differences and mixing angles were measured in completed or currently running experiments, but there are only some experimental hints concerning the CP violation phase [3-6]. The δ_{CP} value may be probed by comparing ($\nu_\mu \rightarrow \nu_e$) and ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) appearance probabilities. The explicit formula for these contains CP-violating term, proportional to $\mp\sin(\delta_{CP})$, where sign distinguishes neutrinos and anti-neutrinos. If $\delta_{CP} = 0$ or π the CP symmetry is conserved and appearance probabilities in vacuum are the same. For $\delta_{CP} = \pm\frac{\pi}{2}$ there is maximal CP violation. In case of T2K baseline and beam energy the asymmetry between neutrinos and anti-neutrinos appearance probabilities is of the order of ~30%. Matter effects [7] also introduce a difference between neutrinos and anti-neutrinos, but for T2K this has smaller impact of the order of ~10%.

2. – T2K experiment design and analysis strategy

The T2K experiment [8] is a long baseline neutrino oscillation experiment located in Japan, using a neutrino beam generated at J-PARC accelerator complex. It is sensitive to the $\theta_{23}, \theta_{13}, \Delta m^2_{23}$ and δ_{CP} parameters. The oscillations are studied by measuring neutrino interactions in near detector complex 280 meters from the beam source and in far detector Super-Kamiokande 295 km away. The experiment started taking data in 2010, one of its finest achievements was discovery of $\nu_\mu \rightarrow \nu_e$ appearance in 2013. [9]

In fig. 1 there is a general scheme of how the (anti-)neutrino beam is produced in J-PARC and forwarded to near and far detector. The very first stage of this process is interaction of 30 GeV proton beam with carbon target. In this process several types of secondary particles are produced, in particular pions and kaons. The target is located inside magnetic horns, which are designed to focus pions into the decay volume. Horns may work in two modes: so-called Forward Horn Current (FHC) and Reversed Horn Current (RHC) when π^+ or π^- are focused, respectively. Inside the decay volume $\pi^+(\pi^-)$ decays into $\mu^+(\mu^-)$ and $\nu_\mu(\bar{\nu}_\mu)$. By choosing FHC or RHC mode it is therefore possible to obtain beam dominated by ν_μ or $\bar{\nu}_\mu$. The beam dump stops most non-neutrino particles

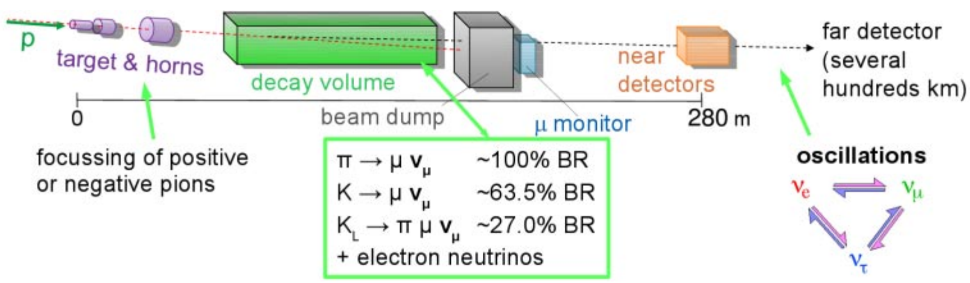

Fig. 1. – Production of (anti-)neutrino beam in T2K.

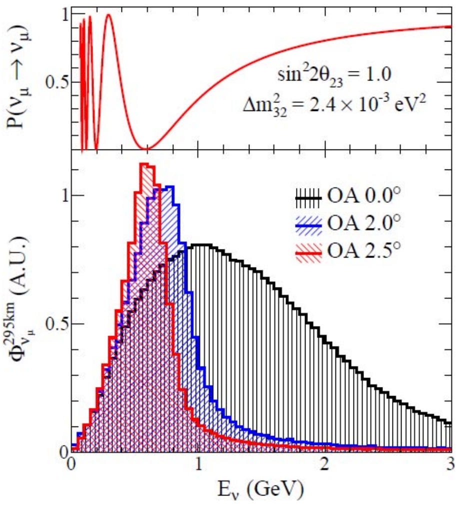

Fig. 2. – Muon neutrino disappearance probability and beam flux at T2K far detector as a function of neutrino energy.

and μ monitor measures the direction and intensity of outgoing muons, which allows for indirect monitoring of neutrino beam.

T2K is an off-axis experiment. The far detector and one of the near detectors are measuring neutrinos deviated by 2.5° from the main beam axis. The energy spectrum of such neutrinos is much more narrow than for on-axis beam. This strategy enhances sensitivity to oscillation effect at the far detector (fig. 2) and reduces background. Around T2K off-axis beam peak (∼600 MeV) mostly CC quasielastic (CCQE) interactions occur.

The near detector complex is located 280 meters from the target and consists of on-axis INGRID [10] and off-axis ND280 detectors (fig. 3). INGRID is a cross-shaped detector composed of 16 Fe/scintillator modules and 1 scintillator module. Its task is to monitor precisely direction, profile and intensity of neutrino beam. The statistics is enough to provide daily measurement for nominal beam intensity. The beam center is determined with an accuracy better than 10 cm, which corresponds to 0.4 mrad.

ND280 is a multipurpose detector used to constrain the off-axis flux and neutrino interaction model. The magnetic field of 0.2 T provided by UA1 magnet allows for distinction of negative and positive particles and momentum measurement. The most inner part of ND280 is P∅D (upstream π^0 detector) and tracker, which allows for CC interaction measurements that support oscillation analysis. The tracker consists of two scintillator fine grained detectors (FGDs) [11] and three gaseous time projection chambers (TPCs) [12]. FGDs serve as interaction targets. TPCs allow for particle identification via energy loss dE/dx measurement and provide good track momentum reconstruction. Both P∅D and tracker are surrounded by electromagnetic calorimeters (ECals). Additionally, the magnet is equipped with side muon range detector (SMRD) that detects muon traveling with high angles with respect to the beam direction.

The far detector Super-Kamiokande is a cylindrical Cherenkov detector filled with 50 kton of pure water, equipped with roughly 13000 photo-multiplier tubes (PMTs) (fig. 3). For the oscillation analysis five event samples are selected in the Super-Kamiokande. These are: 1-ring CCQE μ-like/e-like samples in neutrino/anti-neutrino beam modes and 1-ring CC1π e-like sample in neutrino beam mode. The latter one is optimized to select topology with e^- and π^+ produced in the ν_e interaction. Presence of π^+ is

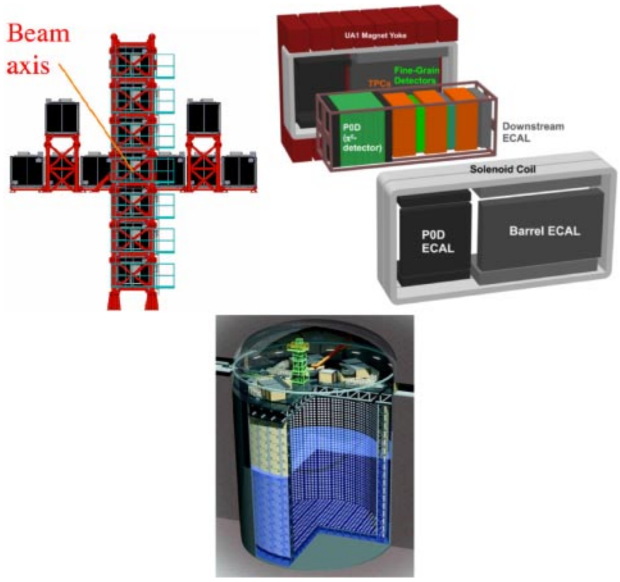

Fig. 3. – Detectors used in T2K experiment. Top left: On-axis near detector INGRID. Top right: Off-axis near detector ND280 (exploded view). Bottom: Far detector Super-Kamiokande.

identified by time-delayed electron decay signature. Super-Kamiokande allows for a very good separation between $\mu^{\pm}$ and $e^{\pm}$ based on characteristics of Cherenkov light ring. In particular, μ-like rings have rather sharp edges, while e-like rings are more fuzzy (fig. 4). This is because muon is significantly heavier particle than electron, which is scattered by Coulomb force when propagating in matter.

Oscillation parameters are obtained by fitting the predicted MC events rate and energy spectrum in the far detector to the actual measured signal. The fit is done simultaneously for all five event samples. The MC predictions benefit significantly from the near detector measurements. In order to predict event rate and spectrum in Super-K it is necessary to use cross-section model (based on external cross-section measurements, mostly from MiniBooNE and MINERνA [13]) and neutrino flux model (based on INGRID and beam monitor data as well as external data from NA61/SHINE experiment [14]).

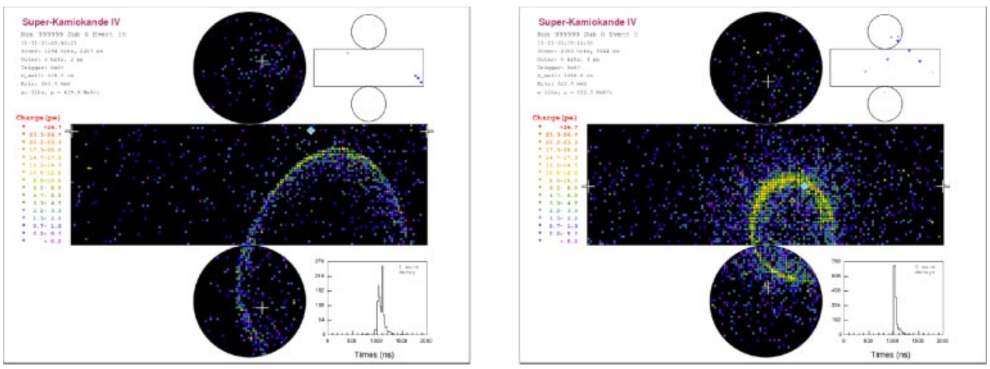

Fig. 4. – MC event display. Left: μ-like ring. Right: e-like ring.

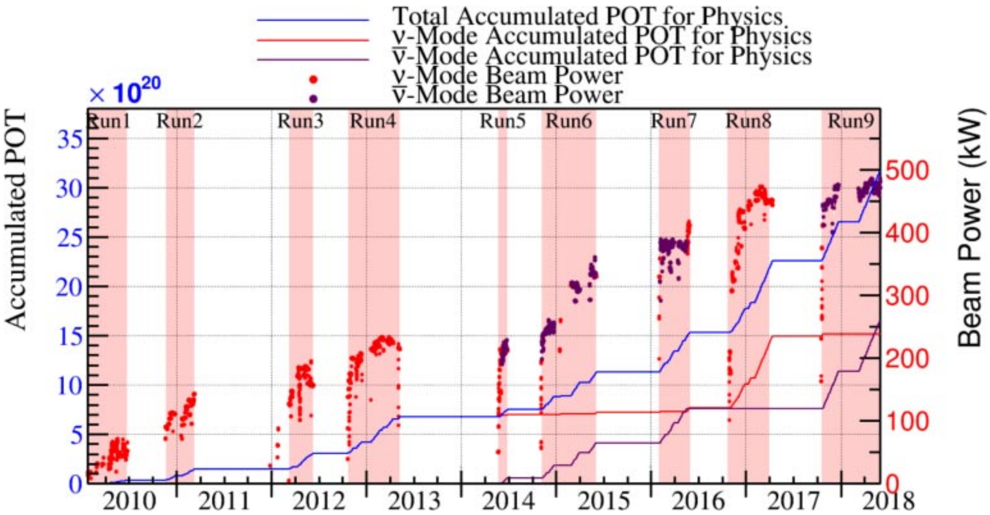

Fig. 5. – Timeline of accumulated POT and beamline power for T2K.

Flux and cross-section models are constrained by fit to data measured in ND280, which decreases model systematic uncertainties by the order of 2.

3. – Results

Since 2010 T2K collected total statistics of 3.16×10^{21} POT. Presented oscillation results are based on 3.13×10^{21} POT with 1.49×10^{21} POT for neutrino beam mode runs and 1.63×10^{21} POT for anti-neutrino beam mode runs. During recent run 9 the anti-neutrino statistics were significantly enhanced (fig. 5).

Rates of predicted and observed event are presented in table I. Four δ_{CP} hypothesis were used to make the predictions, two corresponding to CP-conservation and two corresponding to maximal CP-violation.

The predicted rate of μ-like events is not varying much for different δ_{CP} values, since the oscillation probabilities $P(\nu_\mu \to \nu_\mu)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ are not δ_{CP} sensitive. On the other hand, $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ probabilities are much more sensitive to CP violation and the predicted rate of e-like events is changing significantly for different δ_{CP}.

TABLE I. – *Data event rates compared with predicted MC event rates for different δ_{CP} hypothesis. Normal Hierarchy is assumed.*

Sample	MC predicted rate				Data	MC syst.
	$\delta_{CP} = -\frac{\pi}{2}$	$\delta_{CP} = 0$	$\delta_{CP} = \frac{\pi}{2}$	$\delta_{CP} = \pi$		uncertainty
ν mode μ-like	272.4	272.0	272.4	272.8	243	5.1%
$\bar{\nu}$ mode μ-like	139.5	139.2	139.5	139.9	140	4.5%
ν mode e-like	74.4	62.2	50.6	62.7	75	8.8%
$\bar{\nu}$ mode e-like	17.1	19.4	21.7	19.3	15	7.1%
ν mode e-like + 1 π^+	7.0	6.1	4.9	5.9	15	18.4%

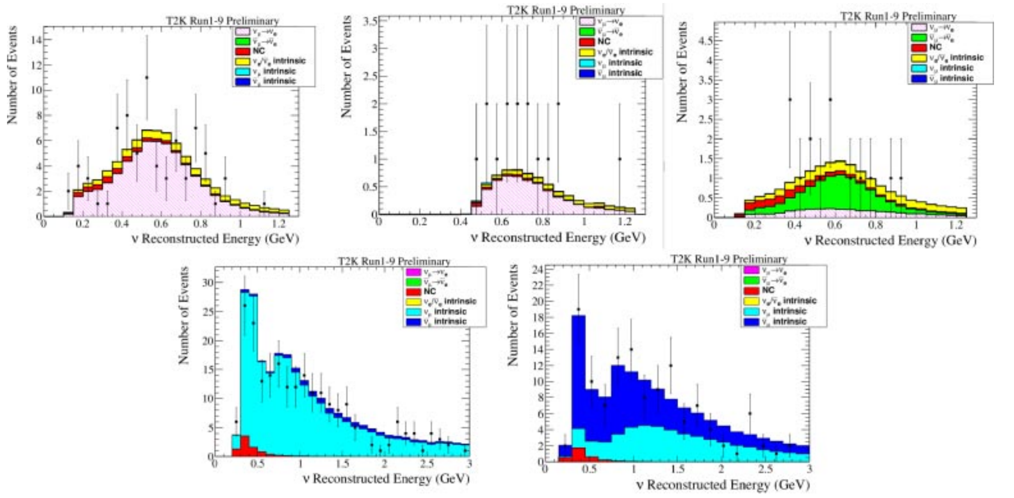

Fig. 6. – Comparison of predicted (histogram) and measured (points) distributions of ν reconstructed energy. For the MC predictions following assumptions were made: Normal Hierarchy, $\delta_{CP} = -\frac{\pi}{2}, \sin^2\theta_{23} = 0.528, \sin^2\theta_{13} = 0.0212$.

The best agreement among presented δ_{CP} hypothesis is for $\delta_{CP} = -\frac{\pi}{2}$. Distributions of reconstructed ν energy for all samples used in the oscillation fit are presented in fig. 6.

The best fit result is $\delta_{CP} = -1.885 \approx -0.6\pi$ for Normal Hierarchy, with $\pm 2\sigma$ range: [-2.966, -0.628]. For Inverted Hierarchy it is $\delta_{CP} = -1.382 \approx -0.44\pi$, with $\pm 2\sigma$ range: [-1.799, -0.979]. The confidence level intervals were obtained with the Feldman-Cousins method [15]. The plot in fig. 7 pictures $-2\Delta\log L$ as a function of δ_{CP} for both NH and IH scenarios. The hatched regions indicate $\pm 2\sigma$ ranges for the best fit results. Both CP-conserving values $\delta_{CP} = 0, \pi$ are excluded at 2σ level. The Normal Hierarchy is preferred with 89% posterior probability.

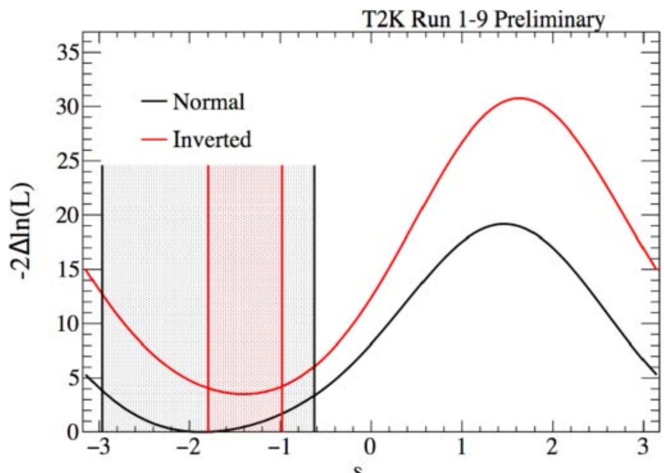

Fig. 7. – $-2\Delta\log L$ distribution with 2σ confidence level intervals around best fit δ_{CP} values. Fit result with reactor constraint.

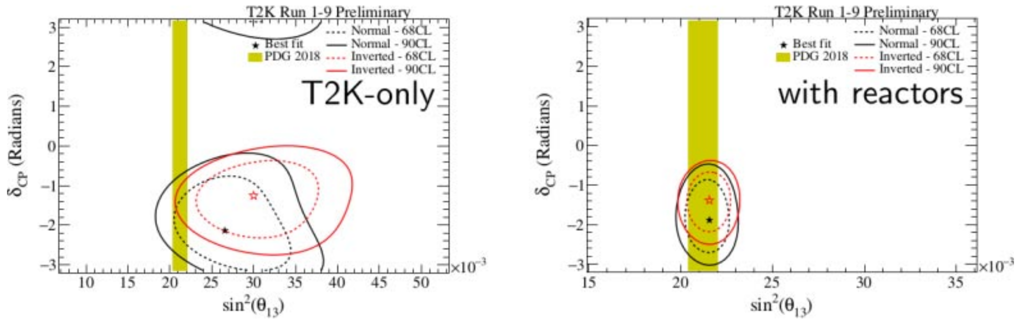

Fig. 8. – Best fit results on δ_{CP} *vs.* $\sin^2\theta_{13}$. Yellow region indicates global result of reactor experiments on $\sin^2\theta_{13} = 0.0212$. Left: Fit result without reactor constraint. Right: Fit result with reactor constraint.

The plots in fig. 8 show results of the oscillation fit on δ_{CP} *vs.* $\sin^2\theta_{13}$. The value of θ_{13} may be treated as a free parameter of the fit or it may be constrained to the measurements of reactor experiments. The T2K results are compatible with reactor ones.

4. – Conclusions and future plans

T2K studies the CP symmetry by comparing the $(\nu_\mu \to \nu_e)$ and $(\bar{\nu}_\mu \to \bar{\nu}_e)$ appearance probabilities. Presented results are based on 3.13×10^{21} POT statistics, which represents an increase of 39% compared to previous oscillation analysis [16]. Current data indicate CP violation at 2σ confidence level for both mass hierarchy hypotheses. The best fit result for $\sin^2\theta_{23} = 0.532$ is consistent with maximal mixing ($\pm 1\sigma$ range: [0.495, 0.562] for NH, [0.497, 0.561] for IH). Normal Hierarchy is preferred with 89% posterior probability.

The collaboration is preparing for T2K phase-II scheduled for 2021-2026. That includes upgrade of near and far detector. Instead of P∅D ND280 will be equipped with two additional TPCs that will increase angular efficiency of track reconstruction and highly granular scintillator detector SuperFGD. [17,18] Super-Kamiokande upgrade will include dissolving gadolinium in the water tank, which will allow for identifying neutrons [19]. Additionally J-PARC proton beam power will be upgraded in order to increase statistics. It is estimated that till 2026 T2K will collect $\sim 20 \times 10^{21}$ POT, which is almost 3 times more than 7.8×10^{21} POT planned for T2K phase-I. Such statistics should allow for observing CP violation at 3σ confidence level if δ_{CP} is close to $\pm\frac{\pi}{2}$. It is also considered to combine T2K-II and NOvA analyses [20]. In such case the sensitivity to CP violation may exceed 4σ.

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REFERENCES

[1] Pontecorvo B., *Sov. Phys. JETP*, **7** (1958) 172.
[2] Maki Z., Nakagawa M. and Sakata S., *Prog. Theor. Phys.*, **28** (1962) 870.
[3] T2K Collaboration (Abe K. *et al.*), *Phys. Rev. D*, **91** (2015) 072010.
[4] T2K Collaboration (Abe K. *et al.*), *Phys. Rev. Lett.*, **118** (2017) 151801.
[5] T2K Collaboration (Abe K. *et al.*), *Phys. Rev. Lett.*, **121** (2018) 171802.
[6] NOvA Collaboration (Acero M. A. *et al.*), *Phys. Rev. D*, **98** (2018) 032012.
[7] Wolfenstein L., *Phys. Rev. D*, **17** (1978) 2369.
[8] T2K Collaboration (Abe K. *et al.*), *Nucl. Instrum. Methods A*, **659** (2011) 106.
[9] T2K Collaboration (Abe K. *et al.*), *Phys. Rev. Lett.*, **112** (2014) 061802.
[10] Abe K. *et al.*, *Nucl. Instrum. Methods A*, **694** (2012) 211.
[11] T2K ND280 FGD Collaboration (Amaudruz P. A. *et al.*), *Nucl. Instrum. Methods A*, **696** (2012) 1.
[12] T2K ND280 TPC Collaboration (Abgrall N. *et al.*), *Nucl. Instrum. Methods A*, **637** (2011) 25.
[13] Wilkinson C. *et al.*, *Phys. Rev. D*, **93** (2016) 072010.
[14] NA61/SHINE Collaboration (Abgrall N. *et al.*), *Eur. Phys. J. C*, **76** (2016) 84.
[15] Feldman G. J. and Cousins R. D., *Phys. Rev. D*, **57** (1998) 3873.
[16] T2K Collaboration (Magaletti L.), *Nuovo Cimento C*, **41** (2018) 137.
[17] T2K Collaboration (Lamoureux M.), *PoS*, **NuFact2017** (2018) 056.
[18] Mineev O. *et al.*, *Nucl. Instrum. Methods A*, **923** (2019) 134.
[19] Super-Kamiokande Collaboration (Marti-Magro L.), *PoS*, **ICRC2017** (2018) 1043.
[20] van Ngoc T., Son C. V. and Van N. T. H., *Commun. Phys.*, **28** (2018) 337.