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Recent results from T2K and future prospects

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Abstract. The T2K long baseline neutrino oscillation experiment in Japan uses a muon neutrino (antineutrino) beam produced by J-PARC and propagating through 295 km to the Super-Kamiokande water Cherenkov detector. The most recent oscillation results from T2K for neutrinos and antineutrinos are reported here. Both $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance data are analyzed, providing leading results for $\sin^2 \theta_{23}$ and Δm_{32}^2 . When fitting using a prior on $\sin^2 2\theta_{13}$ from reactor measurements, T2K is able to put the first constraints on the CP-violating phase δ_{CP} , disfavours the CP-conserving values 0 and π at 90% C.L. Prospects for the future of T2K are also discussed.

1. Introduction

Since the discovery of atmospheric neutrino oscillations in 1998 by Super-Kamiokande, there has been a lot of interest in the determination of parameters of neutrino sector. Oscillations are parametrized by three mixing angles θ_{12} , θ_{13} , θ_{23} , one CP-violating phase δ_{CP} (present in Pontecorvo-Maki-Nakagawa-Sakata matrix U_{PMNS} , equation 1) and two differences of squared mass $\Delta m_{21}^2 = m_2^2 - m_1^2$ and $\Delta m_{31}^2 = m_3^2 - m_1^2$.

$$U_{PMNS} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \quad (1)$$

Although dedicated experiments as accelerator experiments (K2K, MINOS) and reactor experiments (Chooz, KamLaND) have been measuring lepton mixing parameters quite precisely, there are still some remaining questions:

- * We know only $|\Delta m_{31}^2|$ but what is the sign of Δm_{31}^2 (the so-called mass hierarchy)? If $\Delta m_{31}^2 > 0$ ($m_3 > m_2 > m_1$), hierarchy is called normal. If $\Delta m_{31}^2 < 0$ ($m_2 > m_1 > m_3$), hierarchy is inverted.
- * If θ_{23} is not maximal ($\theta_{23} = 45^\circ$), is θ_{23} larger or smaller than 45° (octant determination)?
- * We want to measure the lepton mixing parameters θ_{ij} as precisely as it has been done in the quark sector, and check if U_{PMNS} is unitary.
- * Is there any CP violation in the leptonic sector ($\delta_{CP} \neq 0, \pi$)? This could be an hint for the explanation of matter-antimatter asymmetry in the early Universe.

2. The T2K experiment

T2K[1] is a long-baseline neutrino oscillation experiment in Japan. It uses a muon neutrino (antineutrino) beam produced in Japan-Proton Accelerator Research Center (J-PARC) located in Tokai, Japan. 30 GeV proton beam is sent on a graphite target producing pions and other mesons. Magnetic horns are used to focus either π^+ or π^- . These pions then travel through a 96 m decay volume and further decay. The T2K neutrino beam can be run in either neutrino mode or antineutrino mode depending if we have focused π^+ or π^- . The predicted flux spectrum is given in figure 1.

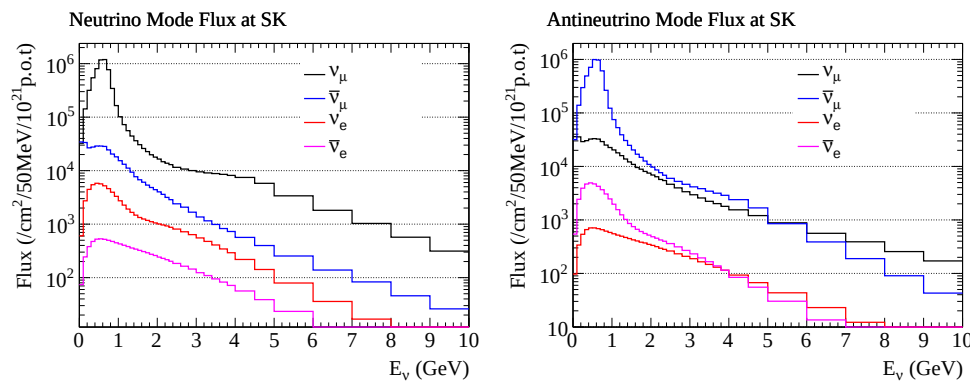


Figure 1: Predicted flux of neutrinos and antineutrinos by species at the SK detector in the absence of oscillation effects for ν -mode (left) and $\bar{\nu}$ -mode (right).

There are three main detectors placed on the beamline:

- * INGRID at 280 m from the target: it is composed of an iron-scintillator sandwich whose goal is to monitor the neutrino flux and its direction [2]
- * ND280 at 280 m: contains several sub-detectors all included in the UA1 magnet (0.2 T). The main tracker volume consists of three Time Projection Chambers (TPCs) and two Fine-Grained Detectors (FGDs) in between. The FGDs are layers of scintillator bars which are used as an active target material (mostly carbon). The second FGD also contain uninstrumented water volumes. The TPCs provides particle identification (PID), momentum measurements and charge identification. ND280 is used to know neutrino flux before any oscillation and constrain flux and cross-section model parameters.
- * Super-Kamiokande at 295 km: it is located 1 km deep in Kamioka mine. It is a 50 kton water Cherenkov detector (22.5 kton fiducial volume). It can distinguish muon and electron (from neutrino charged current interactions) by looking at the shape of Cherenkov ring (fuzzy ring for electron, sharp ring for muon). The energy reconstruction is made with the lepton kinematics assuming a charged current quasi-elastic interaction.

The last two detectors are 2.5° off-axis from the neutrino beam, allowing to have a narrow band muon neutrino beam peaked at 600 MeV, which corresponds to the first oscillation maximum at Super-Kamiokande.

T2K is designed to look at muon neutrino/antineutrino disappearance and electron neutrino/antineutrino appearance. The approximated oscillations formulae (first order in $\alpha = |\Delta m_{21}^2/\Delta m_{31}^2|$, no matter effect) are given in equations 2 and 3, where $\hat{\Delta}_{31} = \frac{\Delta m_{31}^2 L}{4E}$ (L the distance travelled, E the neutrino energy).

$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \hat{\Delta}_{31} \quad (2)$$

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \sin^2 \hat{\Delta}_{31} \quad (3)$$

$$\mp \alpha \sin \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin^2 \hat{\Delta}_{31} \\ + \alpha \cos \delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos \hat{\Delta}_{31} \sin \hat{\Delta}_{31}$$

with a sign - for neutrino and a sign + for antineutrino in the second term.

T2K is sensitive to θ_{23} , θ_{13} , Δm_{31}^2 and δ_{CP} . the sensitivity to δ_{CP} is given by the observation of the asymmetry between neutrino and antineutrino oscillations: $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

3. Analysis method

In order to extract the oscillation parameters, it is needed to constrain flux and cross section parameters using near detectors data and external measurements.

Thanks to the ND280 constraints, uncertainties on the number of events at Super-Kamiokande have been reduced from $\sim 12\%$ to $\sim 5\%$ for muon-like channel and from $\sim 12\%$ to $\sim 7\%$ for electron-like channel.

Several methods are then used to fit oscillation parameters, e.g. Feldman-Cousins (whose results are detailed below) or Markov Chain Monte Carlo (MCMC).

4. Results

T2K has been running since 2010 and has started running in antineutrino mode since summer 2014. Up to May 29, 2016, it has acquired a total of $\sim 1.5 \times 10^{21}$ POT, equally split between neutrino mode (7.48×10^{21} POT) and antineutrino mode (7.47×10^{21} POT). The most recent results are given in a joint analysis of $\nu_\mu - \bar{\nu}_\mu$ disappearance and $\nu_e - \bar{\nu}_e$ appearance.

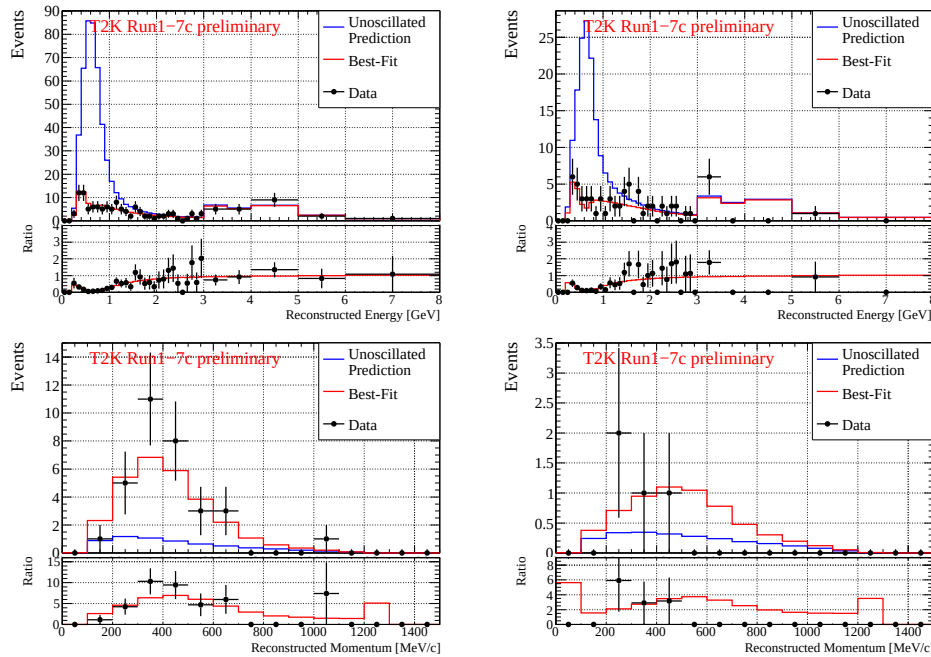


Figure 2: Left: reconstructed energy distributions for ν_μ (top) and ν_e (bottom) candidates observed in ν -mode. Right: corresponding distributions for $\bar{\nu}$ -mode

The observed spectra for muon-like and electron-like events, in neutrino and antineutrino modes, are given in figure 2. The expected number of ν_μ (respectively $\bar{\nu}_\mu$) events without oscillation is 521.8 (184.8), while the observed number is 135 (66), showing a clear sign of disappearance. The best fit values for oscillation parameters are then: $\sin^2 \theta_{23} = 0.532^{+0.046}_{-0.068}$, $\Delta m_{32}^2 = 2.545^{+0.081}_{-0.084} \times 10^{-3} \text{ eV}^2$ ($\sin^2 \theta_{23} = 0.534^{+0.043}_{-0.066}$, $\Delta m_{32}^2 = 2.510^{+0.081}_{-0.083} \times 10^{-3} \text{ eV}^2$) for Normal Hierarchy (Inverted Hierarchy). See figure 3a.

For the appearance analysis, $6.1 \nu_e$ ($2.3 \bar{\nu}_e$) events are expected in the case of no oscillations in neutrino (respectively antineutrino) mode, and the measured number of events is 32 (4). The results of the global fit for $\sin^2 \theta_{13}$ and δ_{CP} are presented figure 3b. It can be stated that the T2K measurement of θ_{13} is in agreement with the value from reactors.

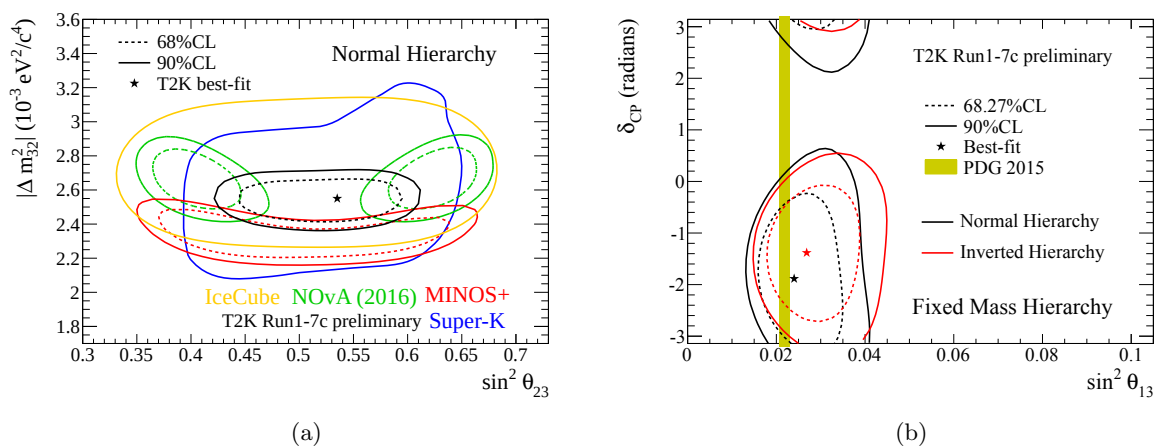


Figure 3: The measured T2K confidence regions for oscillation parameters with the full T2K data set.

(a) $\sin^2 \theta_{23}$ vs Δm_{32}^2 compared to the other experimental results;

(b) $\sin^2 \theta_{13}$ vs δ_{CP} compared with the measurement of θ_{13} by reactor experiments (yellow bar).

When applying the reactor constraint on θ_{13} , T2K is able to provide the first constraint on the CP-violating phase δ_{CP} (see figure 4). In the case of normal hierarchy (inverted hierarchy), the 90% confidence level interval is $-3.13 < \delta_{CP} < -0.39$ ($-2.09 < \delta_{CP} < -0.74$).

We can conclude that T2K favours $\delta_{CP} \sim -\pi/2$ (Normal Hierarchy) region, and disfavors $\delta_{CP} = 0$ at 2σ and $\delta_{CP} = 0, \pi$ at 90% C.L.

5. Prospects

T2K original goal was to reach a total of 7.8×10^{21} protons on target (POT) in 2021, split between neutrino and antineutrino modes. An extension of the T2K running up to 2026, to achieve 20×10^{21} protons on target, is under consideration[5]. An upgrade of the J-PARC beam is needed, in order to reach a projected beam power of 1.3 MW.

The primary goal of this extension (T2K-II) is to achieve $> 3\sigma$ sensitivity for CP violation in electron (anti)neutrino appearance. Figure 5 shows the expected significance of excluding CP conservation ($\delta_{CP} = 0, \pi$) as a function of delivered POT for true $\delta_{CP} = -\pi/2$. It also clearly shows the impact of the current systematic errors on the sensitivity. A near detector upgrade is under consideration to reduce these errors.

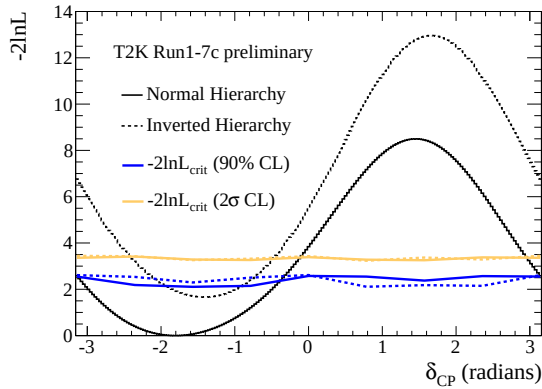


Figure 4: Measured $\Delta\chi^2$ distributions as a function of δ_{CP} and mass hierarchy with the full Run 1-7c data set. The “Feldman-Cousins” method is used to set the $\Delta\chi^2$ critical values. The reactor constraint is applied.

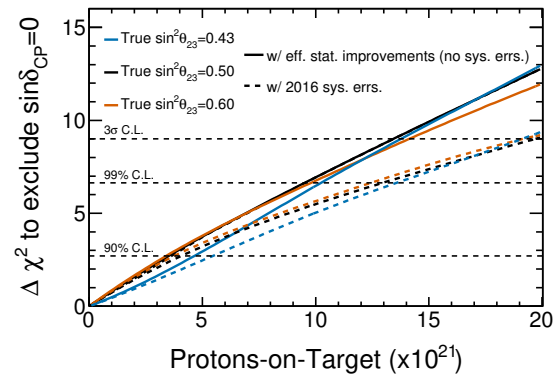


Figure 5: Sensitivity to CP violation as a function of POT for T2K Phase 2 with predicted 2016 systematic errors. The $\delta_{CP} = -\pi/2$ and normal mass hierarchy are assumed to be true. Preliminary plot.

6. Conclusion

Results from the first fully joint analysis across all four neutrino oscillation modes, with $7.48(7.47) \times 10^{21}$ POT in neutrino (antineutrino) mode, have been presented. It is producing the world leading measurements of θ_{23} and has put first constraints on δ_{CP} . T2K data seems to favour $\delta_{CP} \sim -\pi/2$ with normal hierarchy. The experiment will continue running and interesting results are expected in the near future, with T2K “phase 1”, and beyond with the proposed extension.

References

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