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Details of the T2K Neutrino Oscillation analysis

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T2K is a long-baseline neutrino experiment in which a muon neutrino beam produced by J-PARC in Tokai is sent 295 km across Japan to the Super-Kamiokande detector [1]. The experiment studies neutrino oscillations via the disappearance of muon neutrinos and the appearance of electron neutrinos. T2K has conclusively observed muon neutrino to electron neutrino oscillations, opening the door to the observation of CP violation in the lepton sector. Since 2014, the experiment has run alternating neutrino and antineutrino beams in order to precisely measure the corresponding oscillation probabilities, resulting in leading measurements of the muon antineutrino disappearance parameters and results on CP violation in the lepton sector. Different oscillation analyses are performed. They differ in the adopted statistical approach, either frequentist or bayesian, and the kinematical variables used for the analysis templates. In this talk, we will present recently-updated results, focusing on the details of the oscillation analysis methods.

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T2K is a complex two-detector experiment: an (anti)neutrino beam peaked at 600 MeV is measured in two locations: a near detector (ND280), placed 280 m away from the neutrino source, that measures the (anti)neutrino rate and spectrum unaffected by oscillations and a far detector (Super-Kamiokande), 295 km away, where the oscillation probability is near maximal. In this document the methods used in the latest oscillation analysis are described. Complementary information about the latest T2K results can be found in [2, 3]. The analysis strategy consists of several steps and includes the data collected until summer 2018. First the ND280 data are fitted in order to constrain the detector, neutrino flux and cross-section systematic uncertainties, represented by a different set of fit parameters. The fit of the ND280 data produces as output the best-fit values of the systematic parameters and a covariance matrix describing the parameter correlations. Then the constrained flux and cross-section parameters are used in the far-detector analysis to improve the sensitivity to the oscillation parameters. More details about the statistical methods used in the oscillation analyses can be found in [4].

Near Detector data analysis ND280 is a magnetized detector and it allows to measure the lepton charge and separate ν from $\bar{\nu}$ events. Depending on the beam configuration, the event samples are divided into ν-like in ν-beam mode, $\bar{\nu}$-like in $\bar{\nu}$-beam mode and ν-like in $\bar{\nu}$-beam mode and further subdivided into different ν charged-current (CC) topologies, based on the number of reconstructed candidate pions (π) in the event: CC 0π, CC 1π, CC-Others for ν selection and CC 1-Track, CC $>$ 1-Track for $\bar{\nu}$ event selection. A joint fit of all the ND280 data samples is performed: the binned negative log-likelihood is minimized over all the systematic parameters. The results of the ND280 data show an agreement between observed and predicted spectra within 1 standard deviation for both the flux and cross-section parameters.

Far Detector data analysis Since the far detector is not magnetized, the event selection does not change for different beam polarities. Five event samples are selected by applying the CCQE $\mu^{\pm}$-like and CCQE $e^{\pm}$-like selections both in ν and $\bar{\nu}$ beam mode and the CC1π $e^{\pm}$-like selection in ν beam mode. Thanks to the fit of the ND280 data, the systematic uncertainties to the oscillation analysis are reduced from 12–17% down to 4–9% (fractional on total number of events), depending on the event sample topology. Three different analysis approaches are used in parallel to extract constraints on the neutrino oscillation parameters from the data. While all the analyses use templates parametrized in ν reconstructed energy for the $\mu^{\pm}$-like samples, they differentiate for the different kinematical distributions used in the $e^{\pm}$-like samples: the lepton reconstructed angle (ν and $\bar{\nu}$ interactions partially populate different lepton angular regions) versus either the reconstructed ν energy or the lepton momentum. In all the analyses a binned negative log-likelihood function is used of the oscillation parameters of interest ($-2\Delta \ln L$) that converges to a $\Delta\chi^2$ distribution. The statistical methods are different. Two analyses use a hybrid-frequentist approach (nuisance parameters are "marginalized", i.e. integrated [5]) and confidence intervals are produced as a function of the parameters of interest, constraining the systematic uncertainties with the output of the ND280 data fit. On the other hand, another analysis adopts a fully-Bayesian Monte Carlo Markov Chain (MCMC) approach where credible intervals are obtained by fitting the near and far detector samples simultaneously. In all the analysis the oscillation parameters $\sin^2\theta_{13}$, $\sin^2\theta_{12}$ and Δm^2_{21} are constrained with [6]. All the analysis results show very good agreement.

In order to understand the impact of new ν-interaction models not yet implemented in the analysis, "fake-data" studies are performed (see fig. 1): both near- and far-detector MC fake-data sets, which are consistent with the new models, are produced and the full oscillation analysis chain is performed. If the bias in the sensitivity confidence intervals of the oscillation parameters obtained by fitting the fake-data set and the Asimov-data (i.e. nominal MC [7]) is larger than 25% of the total uncertainty or 50% of the systematic uncertainty, additional "ad-hoc" uncertainties are introduced. After the study a new systematic uncertainty was added to account for mis-modeling of the binding energy as well as a Gaussian smearing of the likelihood as a function of Δm^2_{32}.

The search for $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance, predicted by the PMNS matrix, is performed by introducing a new parameter β, that takes only the values 0 or 1 and works as follows: $P(\bar{\nu}_\mu \to \bar{\nu}_e) = \beta \times P_{osc}(\bar{\nu}_\mu \to \bar{\nu}_e)$. All the systematic and oscillation parameters are marginalized. The T2K data do not show any evidence of $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance yet: the p-value to the background $\beta = 0$ (signal $\beta = 1$) hypothesis is 0.233 (0.087).

The joint analysis of all the ν and $\bar{\nu}$ samples is performed. The 1σ confidence intervals are computed with the constant $\Delta\chi^2$ method [6] independently for fixed Normal Ordering (NO) and Inverted Ordering (IO): $\sin^2\theta_{23} = 0.536^{+0.031}_{-0.046}$ for NO ($\sin^2\theta_{23} = 0.536^{+0.031}_{-0.041}$ for IO), $\Delta m^2_{32} = 2.434 \pm 0.064$ for NO ($\Delta m^2_{31} = 2.410^{+0.062}_{-0.063}$ for IO). The T2K data show a preference for nearly maximal CP violation ($\delta_{CP} = -1.82$ radians) and Normal Ordering. The allowed 2σ confidence intervals, computed with the method proposed by Feldman and Cousins [8], are $\delta_{CP} = [-2.91, -0.64]$ for NO and $\delta_{CP} = [-1.57, -1.16]$ for IO and exclude the CP conservation hypothesis, i.e. $\delta_{CP} = 0, \pi$. The CP conserving hypothesis is excluded with a posterior probability of 95%. The posterior probability for the $\sin^2\theta_{23}$ octant as well as the Mass Ordering was computed by assuming the same prior probability for each hypothesis. The NO and $\sin^2\theta_{23} > 0.5$ hypotheses are favored with a posterior probability of, respectively, 0.888 and 0.773, with respect to their counterpart hypothesis, i.e. IO and $\sin^2\theta_{23} < 0.5$. In order to compare the expected sensitivity with the data results, toy MC experiments were produced for several δ_{CP} - NO hypotheses and fitted. It was found that, for $\delta_{CP} = -\pi/2$ and NO as true hypothesis, about 5% of the toy experiments show a fluctuation more extreme than the data, as shown in fig. 1. For about 19% of the toy experiments the CP conservation hypothesis is excluded with a significance of 2σ.

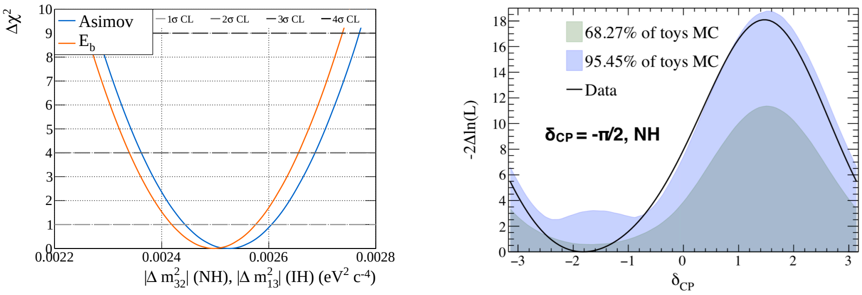

Figure 1: Left: comparison between $-2\Delta\ln L$ distributions (it converges to a $\Delta\chi^2$) obtained with a fake-data set including a variation of the binding energy and the Asimov-data set. Right: toy MC sensitivity compared with the data $-2\Delta\ln L$ distribution. The violet (grey) band contains 95.45% (68.27%) of toys MC.

References

[1] K. Abe et. al (T2K Collaboration), Nuclear Instruments and Methods in Physics Research A 659, 106-135 (2011), 10.1016/j.nima.2011.06.067

[2] Proceeding no. 13 "Results and Prospects from T2K", Steve Dennis

[3] Proceeding no. 62 "The Role of Cross Sections in the Oscillation Analysis: The T2K Experience", Clarence Wret

[4] K. Abe et. al (T2K Collaboration), Phys.Rev. D96 (2017) no.9, 092006

[5] R. D. Cousins and V. L. Highland, Nucl. Instrum. Methods 320, 331 (1992)

[6] C. Patrignani et al. (Particle Data Group Collaboration), Chin. Phys. C 40, 100001 (2016)

[7] G. Cowan, K. Cranmer, E. Gross and O. Vitells, Eur. Phys. J. C (2011) 71: 1554

[8] G. J. Feldman and R. D. Cousins, Phys. Rev. D 57, 3873 (1998)