PROCEEDINGS OF SCIENCE

Neutrino oscillation physics with neutrinos from accelerators

Marco Zito[a,b,*] **for the T2K collaboration**

[a] *Sorbonne Université, Université Paris Cité, IN2P3 (CNRS), LPNHE, 4 place Jussieu, 75005 Paris, France*

[b] *DPhP, IRFU, CEA Saclay 91191 Gif/Yvette CEDEX, France*

E-mail: marco.zito@lpnhe.in2p3.fr

The discovery of non-zero neutrino masses has opened an exciting field in particle physics. Long baseline experiments with neutrinos from accelerators play a special role in this context, with the unique capability to provide information on possible CP violation in this sector. The current status of measurements of neutrino oscillation parameters with neutrinos from accelerator is presented, with emphasis on long baseline experiments and especially T2K.

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*Speaker

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1. Introduction

Neutrinos play a special role in the landscape of contemporary particle physics. Indeed the discovery of neutrino oscillations in 1996-2001 has established non-zero neutrino masses requiring an extension of the Standard Model. As the Particle Data Group [1] explains : "It is not possible to construct a renormalizable mass term for the neutrinos with the fermionic content and gauge symmetry of the SM. The obvious consequence is that in order to introduce a neutrino mass in the theory one must extend the particle content of the model, depart from gauge invariance and/or renormalizability, or do both."

These extensions of the Standard Model range from the simple addition of new neutrino states to the seesaw-mechanism, implying Majorana nature of neutrinos and new heavy neutrinos, providing a natural explanation for the lightness of the neutrino masses. From a purely experimentally point of view one can also notice that the upper limit on the neutrino masses, at a fraction of eV/c^2, sets them far apart from the masses of all other fermions, by six orders of magnitudes. This new mass scale suggests new phenomena. A similar argument can be raised on the basis of the large angles in the neutrino mixing matrix, with a totally different structure from what is observed in the quark sector with the CKM matrix. In addition neutrinos play a major role in cosmology, and this is crucially dependent on their properties. All these considerations motivate high precision studies of currently experimentally accessible neutrino properties to shed light on this sector.

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix, connecting the mass eigenstates to the flavor eigenstates, can be written as the product of three rotations through angles θ_{23}, θ_{13} and θ_{12}, where the second (unitary) rotation depends on a phase $\delta_{\rm CP}$:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

In this equation $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ and we have neglected a diagonal matrix of phases present in the case of Majorana neutrinos, as these phases do not play a role in neutrino oscillations.

The measurement of the three large angles θ_{12}, θ_{23}, and θ_{13} opens the possibility to measure the CP violation parameter $\delta_{\rm CP}$ (for an introduction to the phenomenology of neutrino oscillations and the experimental results in the field see [2]).

In vacuum, the probability of muon neutrino disappearance is

$$P(\nu_\mu \to \nu_\mu) = 1 - \left(\cos^2\theta_{13}\sin^2 2\theta_{23} + \sin^4\theta_{23}\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \tag{2}$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$, m_i being the mass of the neutrino eigenstate i. This channel can be used to measure precisely Δm^2_{31}, $\sin^2 2\theta_{23}$ and also the octant of θ_{23} through the subleading term proportional to $\sin^4\theta_{23}$.

Neglecting matter effects, one can expand the full $\nu_\mu \to \nu_e$ oscillation probability to second

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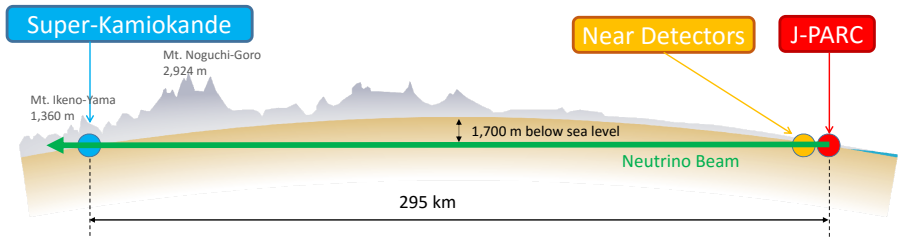

Figure 1: Schematic view of the T2K experiment.

order in the small quantities $\sin\left(\Delta m^2_{21}L/4E\right)$ and $\sin\theta_{13}$:

$$\begin{aligned} P(\nu_\mu \to \nu_e) \;\simeq\; & \sin^2\theta_{23}\sin^2 2\theta_{13}\;\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \cos^2\theta_{23}\sin^2 2\theta_{12}\;\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) \\ & + \frac{1}{2}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\delta_{\rm CP}\;\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)\sin\left(\frac{\Delta m^2_{31}L}{2E}\right) \\ & - \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\delta_{\rm CP}\;\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right). \end{aligned} \quad (3)$$

The first term corresponds to the dominant, Δm^2_{31}-driven oscillations; the second one to the Δm^2_{21}-driven oscillations; the third and fourth terms involve both Δm^2_{21} and Δm^2_{31} and are CP-even and CP-odd, respectively. The fourth term therefore, changing sign for the corresponding antineutrino oscillation, introduces a difference between $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation and provides sensitivity to δ_{CP}.

A long baseline neutrino experiment is based on an intense muon neutrino beam, characterized in a near detector, and propagating in the Earth's crust for hundreds of km before reaching a far detector. It is optimally suited for a CP violation measurement as the magnetic focusing setup allows to select either a muon neutrino beam or a muon antineutrino beam.

2. The T2K Experiment

The T2K experiment [3] consists of three large infrastructures: the neutrino beam and the near detector in the J-PARC laboratory (Tokai), and the far detector in the Kamioka site (fig. 1).

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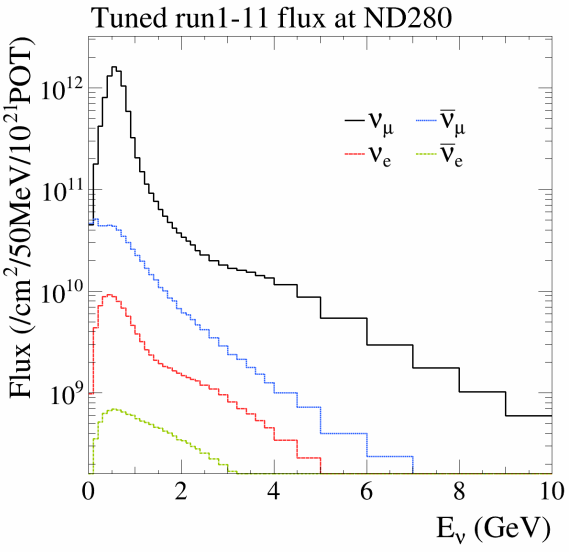

Figure 2: Expected flux of the T2K beam in neutrino mode (positively charged pion focusing).

The neutrino beam is produced by impinging the 30 GeV/c protons from the J-PARC Main Ring onto a graphite target. A system of three magnetic horns focus either positively or negatively charged pions into a 90 m long decay volume, where the pions decay producing muon neutrinos. The Main Ring has recently undergone a major upgrade that enabled to increase the repetition rate from 2.46 s to 1.36 s. Together with other improvements on the beam line and instrumentation, this allows to reach a beam power on target of 800 kW (500 kW previously). Further improvements will allow to reach 1.3 MW by 2027.

T2K is based on the off-axis configuration: the beam direction is deliberately offset by 2.5 degrees with respect to the far detector direction. A kinematic effect due to the two-bodies pion decay enhances the muon neutrino flux at 600 MeV/c (for an off axis angle of 2.5 degrees), corresponding to the first oscillation maximum for the baseline of 295km (fig. 2).

The main measurements on the unoscillated neutrino beam are performed at a detector complex at 280m from the target. INGRID is an on-axis array of scintillator-iron sandwiches aimed at measuring precisely the neutrino beam direction and intensity. A multipurpose magnetized detector ND280 is installed off-axis in the ex-UA1 and NOMAD magnet, donated by CERN, and producing a magnetic field of 0.2 T. It comprises three large TPC based on Micromegas detectors, and two scintillator based detectors (FGD) acting as instrumented target for neutrino interactions.

A major upgrade of ND280 has recently been installed in 2023-2024, comprising two large High-Angle TPC based on resistive Micromegas, and a Super-Fine-Grained Detector (SFGD). SFGD is a 2 ton active scintillator based on 2 millions scintillator cubes, optically separated, each read out by three orthogonal optical fibers. SFGD provides a highly granular picture of the neutrino interactions. It enables to detect neutrons and low momentum protons, down to 300 MeV/c. The High-Angle TPCs allow to track charged particles emitted at high angles in neutrino interactions. They are based on a pad-partout scheme, and provide a space point resolution per column around 200 μm. This allows momentum reconstruction and particle identification through dE/dx (8% resolution for MIP), especially useful for electron-muon separation. An event display of a neutrino

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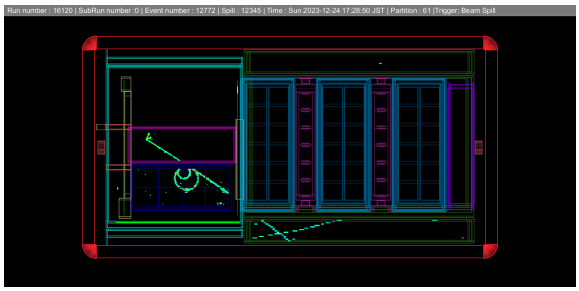

Figure 3: Event display of a neutrino interaction in the ND280 upgraded detectors.

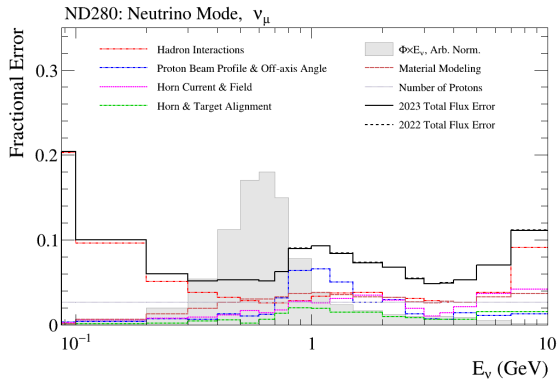

Figure 4: Uncertainty on the T2K neutrino flux using the NA61/SHINE hadro-production data with the T2K replica target. The shaded histogram shows the expected neutrino flux.

interaction in the upgraded detectors is shown in fig. 3.

The far detector of T2K is Super-Kamiokande, a 50 kt water Cherenkov detector operated since 1996. It provides angle and energy reconstruction of charged particles as well as electron-muon identification based on the features of the Cherenkov ring. It has been recently upgraded by adding a gadolinium salt to the ultrapure water (0.03 % in 2022), enhancing neutron tagging.

3. The T2K Oscillation Analysis Method and Results

The results presented here are based on T2K runs 1 to 11 for a total of 2.14 10^{21} Proton on Target (POT) in neutrino mode and 1.63 10^{21} POT in antineutrino mode. The reader can refer to [4] for a detailed description of the T2K analysis pipeline.

The T2K analysis starts with the neutrino flux prediction, based on the proton beam measurement and the results of the NA61/SHINE experiment at CERN. This is a dedicated hadroproduction experiment at CERN using also a T2K replica target. It provides accurate measurements of pion and kaon production cross-section and spectra, allowing to reach the unprecedented 5% uncertainty level in the energy region corresponding to the peak of the neutrino flux (fig. 4).

The neutrino-nucleus interaction cross-section is not precisely modeled to date. Indeed, the simple picture of the neutrino interacting with free nucleons is made more complex by nuclear effects, for example nucleon-nucleon nuclear interactions. As a result, the cross-sections have 10-20 % systematic uncertainties. The strategy to mitigate the impact of these uncertainties is to

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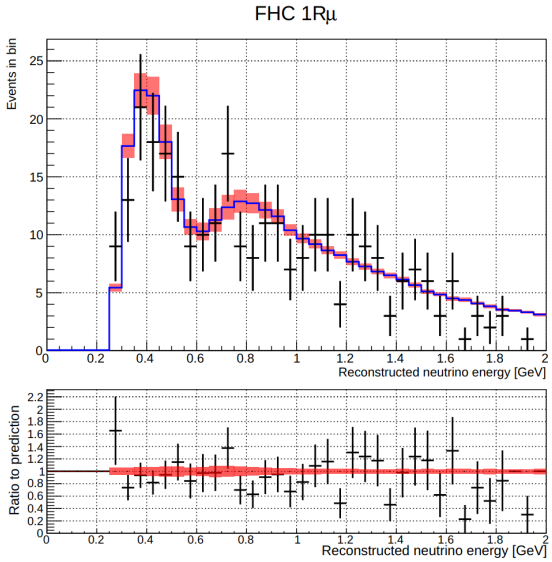

Figure 5: Reconstructed neutrino energy for the sample of one ring muon-like events in Super-Kamiokande in neutrino mode together with the fitted distribution.

use the data of the near detector to constrain the neutrino interaction rate. In T2K, large neutrino interaction samples at the near detector are selected in several final state topologies. For instance a sample of interactions with a muon in the final state and no reconstructed pions is used to constrain the Charged-Current Quasi Elastic (CCQE) channel. The combined fit of the flux and cross-section parameters with these near detector data reduces the uncertainty on the number of events expected at Super-Kamiokande from 15 % to 3-5 %.

Six samples are selected at Super-Kamiokande, with a timing compatible with beam-produced events :

- One ring muon-like and electron-like events in neutrino mode. These samples are enhanced in CCQE interactions and capture the $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ oscillation channels respectively.
- One ring muon-like and electron-like events in anti-neutrino mode. These samples are also enhanced in CCQE interactions.
- Two rings muon-like events.
- One ring electron like events with an additional decay electron.

The latter two samples have a large fraction of neutrino charged current interactions with the production of one pion.

Finally the number of observed events at SuperKamiokande in these samples is compared to the number of expected events and this allows to fit the oscillation parameters. Two illustrative samples at Super-Kamiokande are shown in fig. 5 (one ring muon) and fig. 6 (one ring electron).

As can be seen in Eq. 3, the effect of the CP-violating term $\sin\delta_{CP}$ is to induce a difference in the appearance probability of $\nu_\mu \rightarrow \nu_e$ with respect to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. The T2K ν_e appearance results

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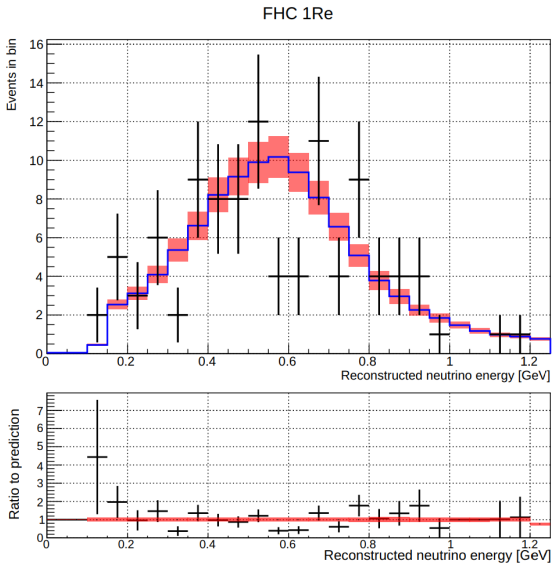

Figure 6: Reconstructed neutrino energy for the sample of one ring electron-like events in Super-Kamiokande in neutrino mode together with the fitted distribution.

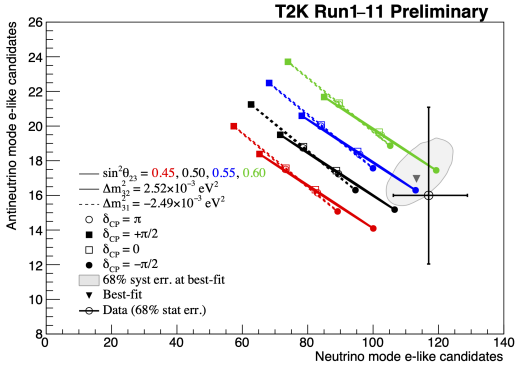

Figure 7: T2K oscillation results (point with error bars) in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ versus $\nu_\mu \rightarrow \nu_e$ plane. The lines show the expectations for various values of δ_{CP} and $\sin^2\theta_{23}$ (the inverted ordering corresponds to the dashed lines).

can be illustrated in the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ versus $\nu_\mu \rightarrow \nu_e$ plane as shown in fig. 7. The data show a weak preference for normal mass ordering and δ_{CP} close to - $\pi/2$. At 2 σ CL the CP-conserving values are excluded (fig. 8).

4. Combined Fits

The data of T2K and NOvA [5], a long-baseline neutrino oscillation experiment in US, have been combined in a common fit, first presented at the recent Neutrino 2024 conference [6]. With respect to the combinations of these results performed by the wider community, this fit uses the full multi-dimensional likelihoods of each experiment. The procedure has been thoroughly validated.

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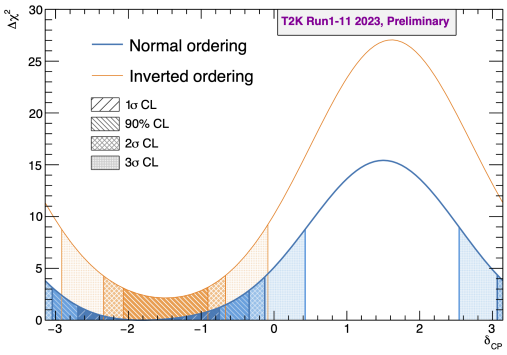

Figure 8: T2K oscillation results showing the $\Delta\chi^2$ distribution versus δ_{CP}. The shaded areas show the confidence intervals.

Special studies have been carried out to check the impact of correlated systematic uncertainties. An article presenting the methods and the results is in preparation and will be submitted soon.

A joint measurement of neutrino oscillation parameters has been performed by the T2K and Super-Kamiokande collaborations, using atmospheric and beam neutrino data-[7]. A common interaction model and correlated detector systematic uncertainties are used. While the constraints on the oscillation parameters are still limited, this first joint analysis is a step towards the combined fits in preparation by the next generation neutrino oscillation experiments.

5. Next generation long baseline experiments

While the present generation of long baseline neutrino oscillation experiments, T2K and NOνA is still taking data and will do so for the next few years, it is clear that these measurements are and will be statistically limited. A new generation of experiments has been approved and is in construction.

Hyper-Kamiokande [8] is based on the same beam as T2K, and the same baseline, with a 260 kt Water Cherenkov far detector. It is currently under construction and will start operation in 2027 and will provide $\nu_\mu \rightarrow \nu_e$ samples larger than 1000 events, at least an order of magnitude more than T2K.

DUNE [9] is a 1300 km long baseline experiment under construction in US with a beam from FNAL to the underground Sanford laboratory in South Dakota. It will a have a 40 kt liquid argon far detector. With the start of Hyper-Kamiokande and DUNE long baseline experiments will enter a new precision era.

6. Conclusions

The present generation of long baseline experiments has contributed to establishing the 3-neutrinos oscillation paradigm ($\nu_\mu \rightarrow \nu_e$ appearance, precision $|\Delta m^2_{32}|$, θ_{13} in agreement with reactor neutrino experiments). It has established new methods for modeling neutrino-nucleus interactions and performing sophisticated near detector fits. It has unveiled tantalizing hints of

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(possible) CP violation effects, however these measurements are statistically limited. A new generation of experiments, HyperKamiokande and DUNE, is in construction with complementary features. They will bring in precision to solve the remaining open questions.

References

[1] S. Navas et al. (Particle Data Group), "Review of Particle Physics", Phys. Rev. D 110, 030001 (2024)

[2] C. Giganti, S. Lavignac, and M. Zito, "Neutrino oscillations: The rise of the PMNS paradigm", Progress in Particle and Nuclear Physics 98 (2018) 1–54.

[3] K. Abe et al. (T2K Collaboration), "The T2K experiment", Nucl. Instrum. Meth.A 659 (2011) 106-135

[4] K. Abe et al. (T2K Collaboration), "Measurements of neutrino oscillation parameters from the T2K experiment using 3.6 10^{21} protons on target", Eur. Phys. J. C 83, 782 (2023).

[5] M. A. Acero et al. (NOvA Collaboration) "Improved measurement of neutrino oscillation parameters by the NOvA experiment", Phys. Rev. D 106 (3 Aug. 2022), p. 032004.

[6] Wolcott, J. (2024, June 17). "New neutrino oscillation results from NOvA with 10 years of data." Zenodo. https://doi.org/10.5281/zenodo.12704805

[7] K. Abe et al. (Super-Kamiokande and T2K Collaborations), "First joint oscillation analysis of Super-Kamiokande atmospheric and T2K accelerator neutrino data", arXiv:2405.12488.

[8] K. Abe et al. (Hyper-Kamiokande Collaboration), "Hyper-Kamiokande Design Report", https://arxiv.org/abs/1805.04163

[9] B. Abi et al. (DUNE Collaboration), "Far Detector Technical Design Report, Volume I: Introduction to DUNE", JINST 15 T08008 (2020).

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