PROCEEDINGS OF SCIENCE

Recent results and prospects of LBL accelerator experiments

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Recent results in neutrino oscillations obtained in current long baseline (LBL) accelerator experiments T2K and NOνA are discussed. The current status and prospect of the future projects DUNE and Hyper-Kamiokande are presented. The emphasis of the talk is put on a search for CP violation in neutrino oscillations and determination of the neutrino mass ordering.

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1. Introduction

The discovery of neutrino oscillations in experiments with solar, atmospheric, reactor, and accelerator neutrinos has provided compelling evidence for non-zero neutrino masses and leptonic mixing. Oscillation data obtained by now are well described in the framework of three active massive neutrinos which flavour eigenstates ν_e, ν_μ, ν_τ and mass eigenstates 1, 2, 3 with masses m_1, m_2, m_3. Flavour eigenstates and mass eigenstates are related by the 3×3 Pontecorvo-Maki-Nakagawa-Sakata (PMNS) unitary mixing matrix. This matrix is parametrized by three mixing angles $\theta_{12} \sim 34°$, $\theta_{23} \sim 45°$, $\theta_{13} \sim 8.5°$, and a CP-violating phase δ_{CP}. Non-zero masses appear in oscillations as two independent squared-mass differences between mass eigenstates $\Delta \mathrm{m}^2_{21} \simeq 7.5 \times 10^{-5}$ eV^2 and $|\Delta \mathrm{m}^2_{32}| \simeq 2.4 \times 10^{-3}$ eV^2. The sign of $\Delta \mathrm{m}^2_{32}$ is unknown. Both the normal ordering (NO) of neutrino masses, $\mathrm{m}_3 \gg \mathrm{m}_2 > \mathrm{m}_1$, and the inverse ordering (IO), $\mathrm{m}_2 > \mathrm{m}_1 \gg \mathrm{m}_3$ are possible. Unlike quarks, it turned out that the different flavours of neutrinos are strongly mixed. These results have determined the main tasks of current and future accelerator and reactor long baseline experiments: the search for CP violation in the lepton sector of the Standard Model and measurement of δ_{CP}, the determination of the neutrino mass ordering, and precise measurement of oscillation parameters. In the talk, the results of the running LBL accelerator experiments T2K and NOνA, as well as prospects of the future projects Hyper-Kamiokande and DUNE are discussed.

2. Experiment T2K

The T2K experiment [1] uses a pure off-axis (shifted from the direction of the proton beam by 2.5 degrees) quasi-monoenergetic beam of muon neutrinos (antineutrinos) produced by a high-intensity proton beam at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai. The neutrino (antineutrino) spectrum has a peak energy of $\mathrm{E}_\nu \approx 0.6$ GeV tuned to the first oscillation maximum with $\Delta \mathrm{m}^2 \simeq 2.4 \times 10^{-3}$ eV^2. A complex of near neutrino detectors, approximately 280 m from the beam production target (ND280), characterises the T2K neutrino beam before possible oscillations and is used to constraint the uncertainties on the neutrino flux and interactions in the oscillation analysis. A large water Cherenkov detector Super-Kamiokande serves as the far detector for T2K. It is located 295 km from the neutrino production target. Super-Kamiokande is filled with 50 kt of ultra pure water that is optically separated into an inner detector which forms the primary target for neutrino interactions, and an outer detector which serves to veto external backgrounds. Super-Kamiokande uses ∼ 11000 PMTs, each of 20-inch diameter, with a photo-cathode coverage of 40% of the inner detector surface. An outer detector surrounds the inner detector with 2 m thickness of water, equipped with 1885 8-inch PMTs with wavelength-shifting plates. The T2K experiment collected 19.7×10^{20} protons on target (POT) in neutrino mode and 16.3×10^{20} POT in antineutrino mode at the far detector in 2010-2020. Data selected for the oscillation analysis represent the following samples: electron-like (1Re), muon-like (1Rμ) primary Cherenkov ring, and a specific number of delayed triggers relative to the primary interaction, consistent with a Michel electrons from unseen charged muon decays (referred to as "de"). In total, 318 (137) 1Rμ events were accumulated in ν ($\bar{\nu}$)-mode, 96(16) 1Re events were accumulated in ν ($\bar{\nu}$)-mode, and 14 Rede events in ν-mode.

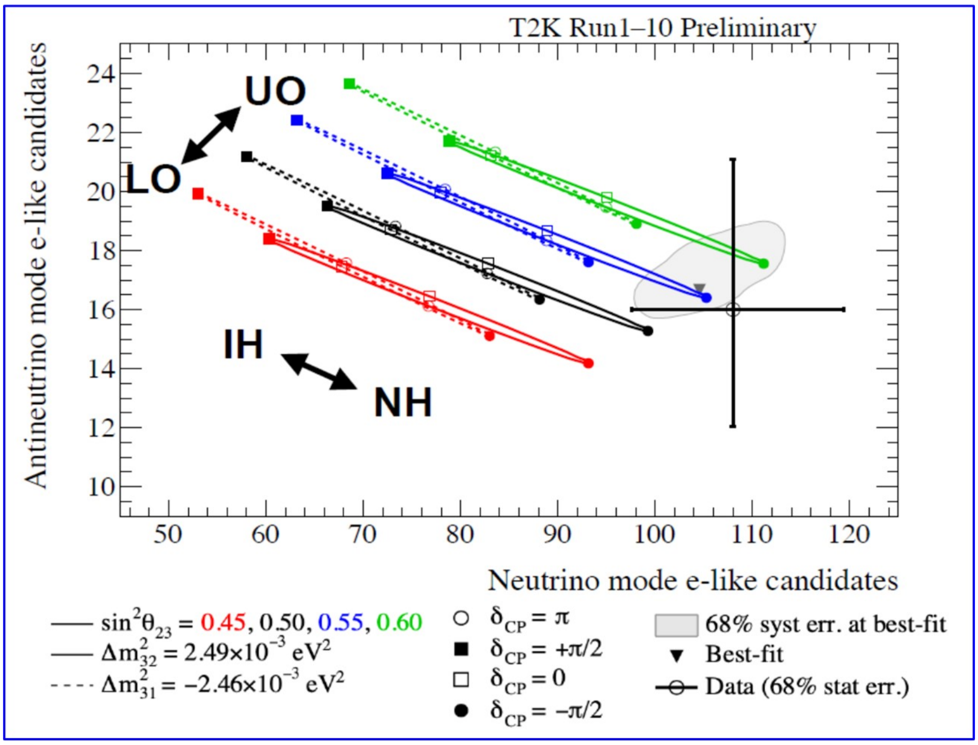

Figure 1: The number of observed electron antineutrino events against the observed neutrino events in the T2K experiment [2]. Error bars are statistical. The predicted number of events for various sets of oscillation parameters are shown by the different coloured ellipses. The triangle point shows the predicted number of events for the best-fit δ_{CP} around maximal CP violation $-\pi/2$, the shaded area contains the predicted number of events around the best-fit δ_{CP} for 68% of simulated experiments.

For direct measurement of CP asymmetry in neutrino oscillations, the comparison between the oscillation probabilities of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ is necessary. The information about CP phase δ_{CP} can be obtained from the total number and the energy spectra of the detected ν_e and $\bar{\nu}_e$ events. For $E_\nu \sim 0.6$ GeV, the baseline of 295 km, $\theta_{13} = 8.5^\circ$, and $\sin^2 2\theta_{23} = 1.0$ the CP asymmetry (including the matter contribution) is:

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq -0.29 \sin\delta_{CP} \pm 0.09. \tag{1}$$

The effect of the CP violating term can be as large as 29%, while the fake CP violating matter effect is ±9%, where "+" - is for the normal mass ordering and "-" is for the inverted mass ordering.

The number of observed electron antineutrino events against the observed neutrino events are plotted in Fig. 1. The comparison of $\sin^2\theta_{13} - \delta_{CP}$ contours with and without the reactor constraint is shown in Fig. 2. The regions are in a good agreement, with a majority of the 1σ regions overlapping, comparable with the reactor constraint. The T2K data favours $\delta_{CP} \sim -\pi/2$, $\Delta m^2_{32} > 0$, and $\sin 2\theta_{23} > 0.50$, i.e. near the maximal CP violation, the normal mass ordering, and the upper octant in the PMNS paradigm, as illustrated in Fig. 3.

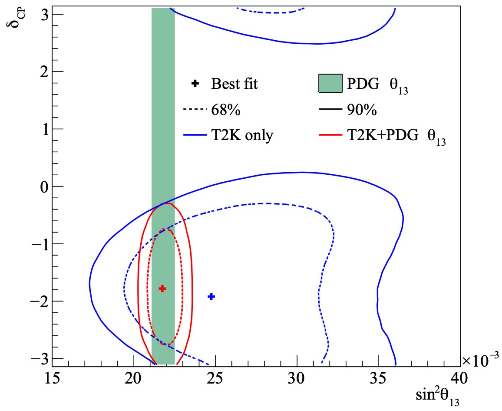

Figure 2: 68% and 90% credible intervals from the marginalised $\sin^2\theta_{13}$ vs δ_{CP} posterior distribution with(red) and without (blue) the reactor constraint (green band) applied, marginalised over both mass orderings.

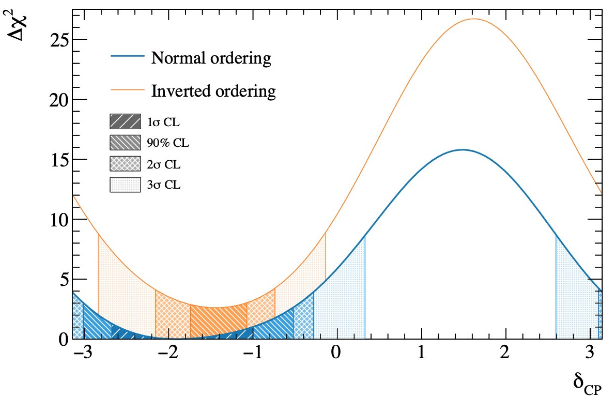

Figure 3: The $\Delta\chi^2$ distribution in δ_{CP} from fitting to the data with the reactor constraint applied. The confidence intervals in the shaded regions are calculated using the Feldman-Cousins method.

3. Experiment NOνA

The NOνA experiment [3] also uses an off-axis beam of muon neutrinos (antineutrinos) produced by 120 GeV protons at the Main Injector beam facility at Fermilab (USA). The energy spectrum has a peak energy at 2 GeV at the near detector. Both the near and the far NOvA detectors are located 14.6 mrad off the central NuMI beam axis. The 290 ton near detector at Fermilab is 100 m underground, shielded from cosmic rays, and the far detector is located on the surface with modest shielding near Ash River, Minnesota, 810 km away from the beam source. These two functionally identical detectors are designed to reduce the effects of systematic uncertainties. Both detectors are tracking calorimeters composed of planes of horizontal and vertical extruded PVC cells filled with liquid scintillator mixed into oil. The light in each cell is collected by looped wavelength-shifting fibers read-out by avalanche photodiodes. The total mass of the far detector is 14 kton, with the active mass being 65% of that.

NOνA collected data from an exposure of 13.6×10^{20} 14 kton - equivalent POT in the neutrino-enriched beam mode and 12.5×10^{20} POT in the antineutrino mode. It was observed 82 electron neutrino events and 33 electron antineutrino events in the far detector. The estimated backgrounds are 26.8 and 14.0 events for neutrino and antineutrino, respectively. Fig. 4 shows the transition probability of $P(\nu_\mu \rightarrow \nu_e)$ against $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ divided into two energy bins of 1.5 and 2.5 GeV. The nearby ellipses show the theoretical values of the transition probabilities for all values of δ_{CP} for both the normal (blue) and inverted (yellow) neutrino mass ordering. As can be seen from Fig. 4, NOvA data falls near the center between the two ellipses. In the case of 1.5 GeV energy bin, the result is in favour of $\delta_{CP} \sim 3/2\pi$ for IO and $\delta_{CP} \sim \pi/2$ for NO. All NOνA data provide the best fit value $\delta_{CP} = 0.82\pi$ for NO, and about 1.5π for IO. Fig. 5 shows NOνA allowed regions in $\sin^2\theta_{23}$ and δ_{CP} and the best fit from T2K. For the normal mass ordering the T2K best fit point lies in a region that NOνA disfavours. However, the T2K allowed region is entirely contained at

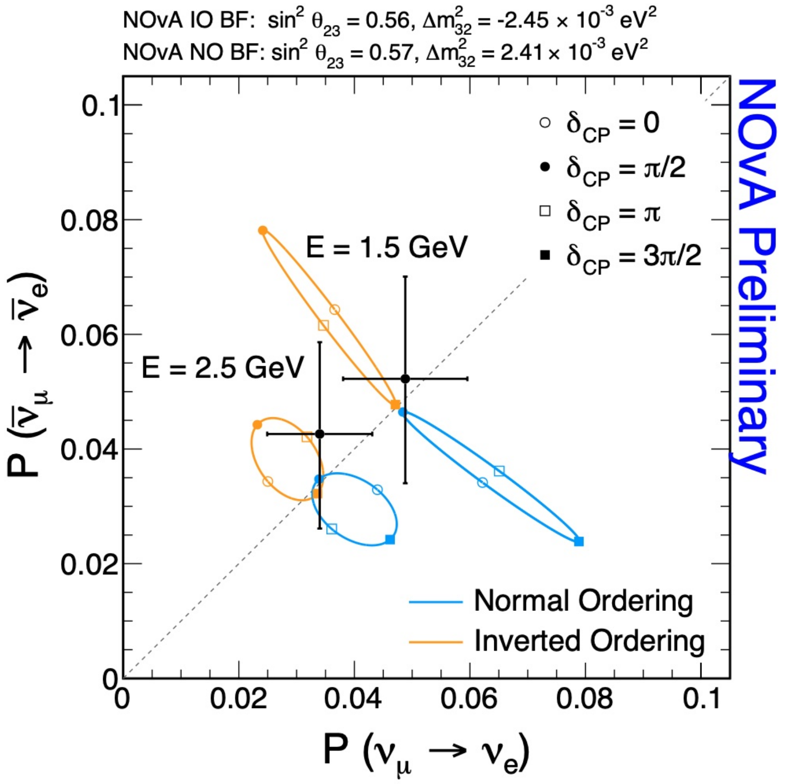

Figure 4: The transition probabilities $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ for different values of δ_{CP} for NO (blue ellipse) and IO (yellow ellipse). The measurements are divided into two energy bins (1.5 GeV and 2.5 GeV) and superimposed [4].

90% confidence level within the corresponding NOνA allowed region in the case of IO. It should be noted that T2K, NOνA, and Super-Kamiokande [6] prefer the normal mass ordering. The global analysis which takes into account oscillation data and neutrinoless double beta decay results prefers the normal neutrino mass ordering with 2.5σ statistical significance, as obtained in [7]. T2K and NOνA will continue data taking for about 3-4 years and can explore CP violation with a sensitivity of about 3σ if $\delta_{CP} \sim -\frac{\pi}{2}(\frac{3\pi}{2})$ and the mass ordering is normal.

It is important to note that the results of measurements of oscillation parameters Δm^2_{32} and $\sin^2\theta_{23}$ by MINOS, T2K, NOνA, IceCube, and Super-Kamiokande are consistent within the 90% confidence level. Fig. 6 shows 90% CL contours and best-fit points Δm^2_{32} and $\sin^2\theta_{23}$ obtained by MINOS, T2K, NOνA, IceCube, and Super-Kamiokande experiments. As can be seen from this Figure, the results of these experiments with accelerator and atmospheric neutrinos are consistent at the 90% level.

4. Future projects Hyper-Kamiokande and DUNE

The Hyper-Kamiokande project [9] includes the neutrino beam obtained with a 1.3 MW proton beam at J-PARC, a complex of near detectors: an upgraded T2K near detector ND280 [8] together with a new Intermediate Water Cherenkov Detector, about 1 km from the neutrino source, and a

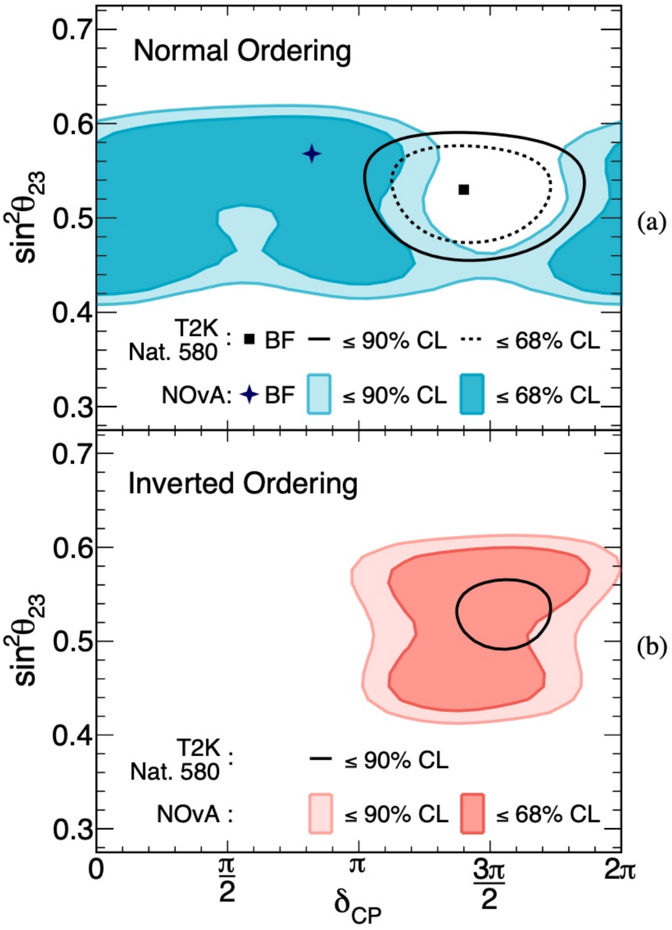

Figure 5: Confidence level contours in the NO (a) and IO (b) [5]. The cross denotes the NOνA best-fit point. Black solid-line and dashed-line contours show allowed regions from T2K.

far detector Hyper-Kamiokande (HyperK). HyperK is a cylindrical tank with a diameter of 68 m and height of 71 m. The total (fiducial) mass of the detector is 258 (187) kton, giving a fiducial mass 8 times larger than Super-Kamiokande. HyperK will be located in Tochibora mine, 8 km south of Super-Kamiokande and 295 km away from J-PARC. The detector is filled with a highly transparent purified water which has a light attenuation length of ∼ 100 m and has a two-layer structure consisting of an inner and an outer water volume (Inner Detector (ID) and Outer Detector (OD)). The ID will be instrumented with 20000 inward facing newly developed high-efficiency 50 cm diameter Hamamatsu R12860 PMTs which have ∼ 2 times higher photon detection efficiency than that of the Super-Kamiokande PMTs. In addition, ID will be equipped with about 1000 multi-PMT modules comprised of 3” PMTs which will enhance the reconstruction potential of the detector. The OD will be instrumented with about 3600 3-inch high-sensitivity PMTs coupled to wavelength-shifting plates to veto entering events such as cosmic ray muons. HyperK will use the water Cherenkov ring-imaging technique to detect charged leptons produced in neutrino interactions on nuclei in water. To study the sensitivity to CP violation, an integrated beam power 1.3MW × 10^8 sec that corresponds to 2.7×10^{22} protons on target (POT) with the 30 GeV J-PARC

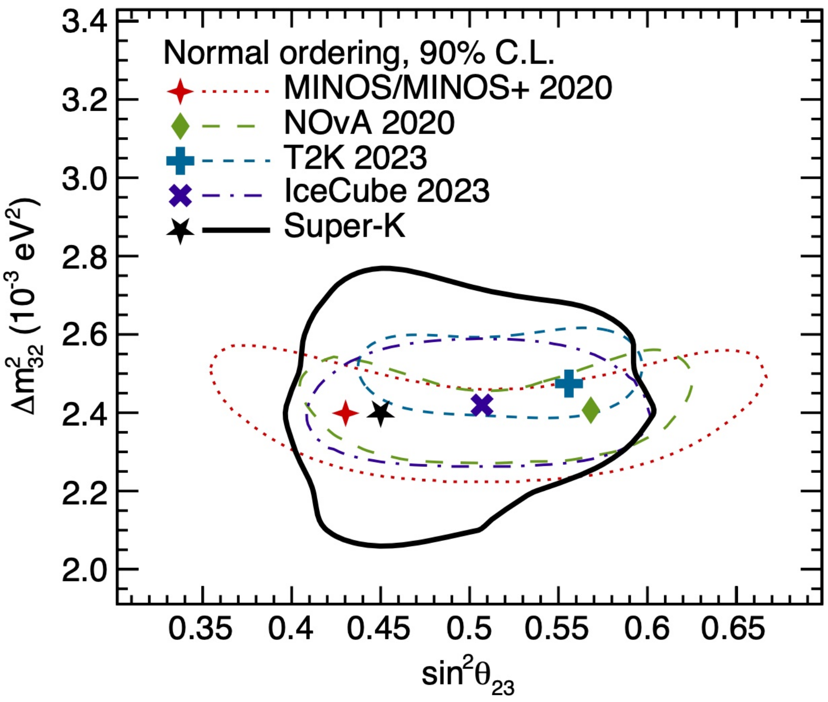

Figure 6: Contours of the 90% CL allowed region for oscillation parameters Δm^2_{32} and $\sin^2\theta_{23}$ for the normal mass ordering. Contours are drawn for each experiment with respect to the best-fit point in the normal mass ordering. Best fit points are indicated with markers for each experiment. See for detail Ref. [6].

proton beam is assumed. The ratio of integrated beam power for neutrino and antineutrino beam mode is fixed $\nu : \bar{\nu} = 1 : 3$. This allows HyperK to detect about the same number of electron neutrino and antineutrino events. The selection criteria of ν_e and ν_μ candidate events are based on those established in the Super-Kamiokande and T2K experiments. The expected significance of exclusion CP conservation ($\sin\delta_{CP} = 0, \pm\pi$) as a function of the true phase δ_{CP} is shown in Fig. 7. As seen from Fig. 7, CP violation in neutrino oscillations can be observed with $\geq 5\sigma$ significance for about 60% of the possible values of δ_{CP} and the exclusion of $\delta_{CP} = 0, \pm\pi$ can be obtained with a significance of about 9σ in the case of maximal CP violation with $\delta_{CP} = -\pi/2$, if systematic error will be reduced to a level of 2.7%.

HyperK does not have a good sensitivity to the mass ordering in oscillation measurements with accelerator neutrino due to a relatively short baseline of 295 km. However, HypeK will accumulate a huge statistics of atmospheric neutrinos. They have in general a longer baseline and higher energies than accelerator neutrinos from J-PARC. Matter-induced parametric oscillations in the energy range of 2-10 GeV lead to a significant enhancement of either the $\nu_\mu \rightarrow \nu_e$ or the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance probability for upward-going neutrinos depending on the mass ordering. Neutrino (antineutrino) oscillations are enhanced for the normal (inverted) ordering. This enhancement leads to appearance probabilities around 50% for both ordering. The separation of atmospheric neutrino data into neutrino-like and antineutrino-like subsets can therefore be used for determination of mass ordering. It is expected that combining accelerator and atmospheric neutrino data HyperK can exclude incorrect mass ordering at $(4-6)\sigma$ depending on the true value of θ_{23} after 10 years of

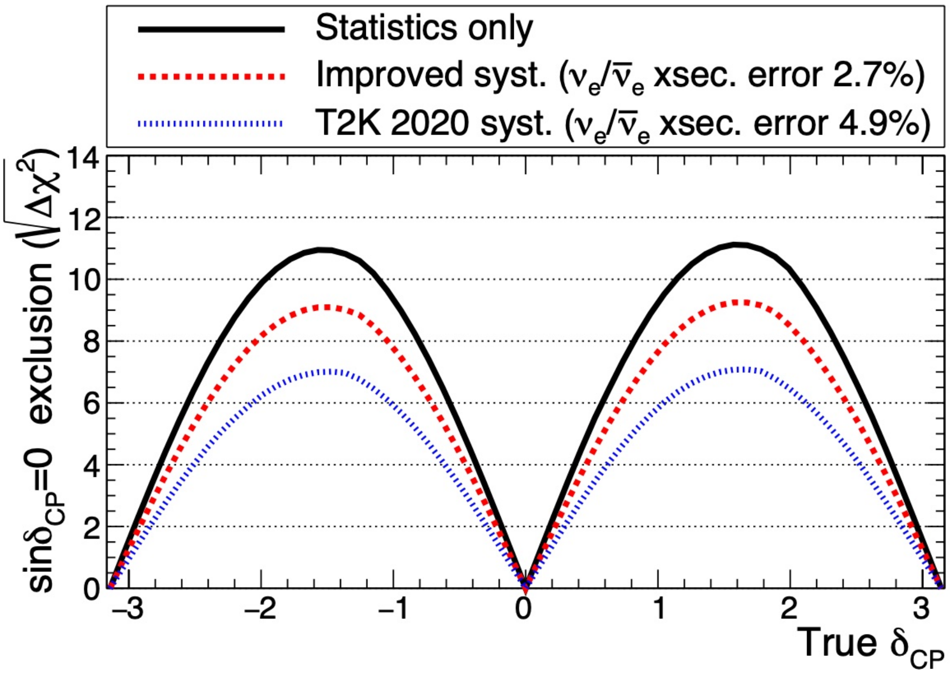

Figure 7: Expected significance to exclude CP conservation (sinδ_{CP} = 0, ±π) for the normal mass ordering by Hyper-Kamiokandre after 10 years of data taking. The effect of experimental uncertainties is presented for three cases: no systematic errors (statistical error only), improved systematics, and T2K 2020 (current) systematics.

data taking. According to the current plan, Hyper-Kamiokande is expected to begin data taking with accelerator neutrinos in 2017.

The Deep Underground Neutrino Experiment (DUNE) [10], which is currently under construction in the US, has a broad physics program including a sensitive search for CP violation in neutrino oscillations, determination the neutrino mass ordering, and precise measurements of neutrino oscillation parameters. The DUNE project includes a high intensity wide band on-axis neutrino and antineutrino beam with neutrino energies of 1- 6 GeV at Fermilab, a complex of near neutrino detectors, and a massive far detector consisting of a set of four 17.5-kton (total mass) Liquid Argon Time Projection Chambers (LArTPCs). This technology provides excellent capabilities for a high-precision reconstruction of complex interaction topologies over a broad neutrino energy range and will provide a powerful complementarity to Hyper-Kamiokande. A 3D millimeter-scale resolution will allow to identify particle types by their dE/dx and by track patterns, e.g., the decays of stopping particles. In addition, the far detector will be instrumented with photon detectors that will provide precise time information and additional calorimetric information. DUNE Phase I is approved with two 17.5 kt LArTPCs: the horizontal drift detector module and the vertical drift detector module. The near detector complex will have movable detectors (NDLAr, TMS) and an on-axis detector SAND. The far detector will be situated about 1500 m underground at about 1300 km from Fermilab. The first neutrino beam of about 1 MW is expected in 2031. Due to the long baseline, DUNE has a very good sensitivity to the neutrino mass ordering. Example of the ultimate

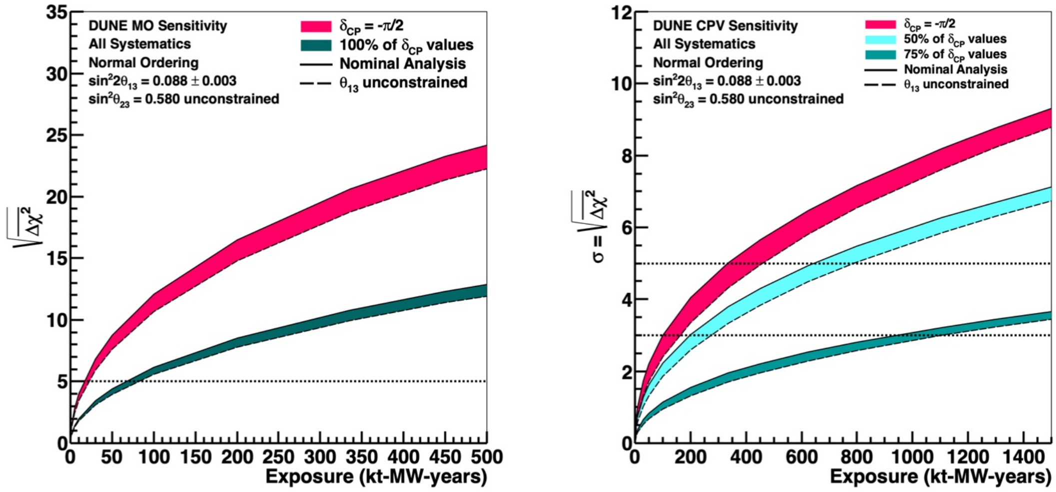

Figure 8: The significance with which DUNE can resolve the neutrino mass ordering (left), and CP violation (right), assuming the true mass ordering is normal. The curves represent different assumptions about the value of δ_{CP}. The width of the bands correspond to the effect of using an external constraint on θ_{13} from reactor experiments. The red curve shows the most favourable case of the maximal CP violation.

physics sensitivity of DUNE to neutrino mass ordering and CP violation are given in Fig. 8. As follows from Fig. 8, more than 5σ mass ordering significance can be reached in 1 year of data taking, if $\delta_{CP} = -\pi/2$, and in 4 years for all δ_{CP} values.

Evaluating the potentials of HyperK and DUNE, one can conclude that HyperK has a higher sensitivity to CP violation due to the shorter baseline and less contamination from fake CP violation induced by a matter effect. However, at the same time, the shorter baseline reduces the sensitivity of HyperK to the mass ordering. On the other hand, the longer baseline of DUNE helps to pin down the mass ordering in this experiment but degrades the sensitivity to CP violation because of a larger matter effect compared to HyperK.

5. Conclusion

The results of T2K and NOνA experiments are well described in the standard 3x3 unitary mixing framework. There is a good agreement between ν_μ and $\bar{\nu}_\mu$ disappearance data of both experiments. The tension arises from the ν_e appearance data. T2K provides a significant hint on the CP violation, whereas NOνA doesn't show the CP violation if the neutrino mass ordering is normal. If the neutrino mass ordering is inverted, the two experiments consistently favour the maximal CP violation. The normal mass ordering are weakly preferred in both experiments. Hyper-Kamiokande and DUNE will be multi-purpose and highly complementary experiments with different neutrino flux, baseline and detector technologies. HyperK and DUNE will definitively determine the neutrino mass ordering, provide the discovery sensitivity to CP violation, and make precision measurements of neutrino oscillation parameters.

References

[1] K. Abe et al., *The T2K Experiment*, *Nucl. Instrum. Meth.* **A659** (2011) 106 [arXiv:1106.1238 [physics.ins-det]].

[2] K. Abe et al., *Measurements of neutrino oscillation parameters from the T2K experiment using* 3.6×10^{21} *protons on target*, *Eur. Phys. J. C* **83** (2023) 782 [arXiv:2303.03222 [hep-ex]].

[3] M. Acero et al., *First measurement of electron neutrino appearance in NOvA*, *Phys. Rev. Lett.* **116** (2016) 15, 151806 [arXiv:1601.05022 [hep-ex]].

[4] M. Frank, *Latest Three-Flavor Neutrino Oscillation Results from NOvA*, PoS, EPS-HEP2023 (2024) 152.

[5] M. Acero et al., *Improved measurement of neutrino oscillation parameters by the NOvA experiment*, *Phys.Rev. D* **106** (2022) 3, 032004 [arXiv:2108.08219 [hep-ex]].

[6] T. Wester et al., *Atmospheric neutrino oscillation analysis with neutron tagging and an expanded fiducial volume in Super-Kamiokande I-V,* arXiv:2311.05105 [hep-ex].

[7] P. F. de Salas et al., *2020 global reassessment of the neutrino oscillation picture*, *JHEP* **02** (2021) 071 [arXiv:2006.11237 [hep-ex]].

[8] K. Abe et al., *T2K ND280 Upgrade - Technical Design Report*, arXiv:1901.03750 [physics.ins-det].

[9] K. Abe et al., *Hyper-Kamiokande Design Report*, arxiv:1805.04163 [physics.ins-det].

[10] R. Acciarri et al., *Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) : Conceptual Design Report, Volume 2: The Physics Program for DUNE at LBNF*, arXiv:1512.06148 [physics.ins-det].