

Precise Measurements of Oscillation Parameters θ_{13} and Δm_{ee}^2

Yuhang Guo, Qingmin Zhang¹

*Department of Nuclear Science and Technology, School of Energy and Power Engineering,
Xi'an Jiaotong University, Xi'an 710049, China*

On behalf of Daya Bay Collaboration

The precision of neutrino mixing angle θ_{13} is of key significance in constraining the leptonic CP phase and testing neutrino oscillation theory. θ_{13} is the smallest and the last known neutrino oscillation angle, and its precise measurements were reviewed in this paper. Its two typical measurement approaches, long-baseline accelerator neutrino experiment and short-baseline reactor neutrino experiment, are summarized. Then, their related typical experiments and the corresponding results were also overviewed. Daya Bay is the first experiment to exclude $\theta_{13}=0$ with a significance of more than 5 standard deviations and has given the most accurate measurement of $\sin^2 2\theta_{13}=0.0841\pm 0.0027(\text{stat.})\pm 0.0019(\text{syst.})$. In addition, $|\Delta m_{ee}^2|=2.50\pm 0.06(\text{stat.})\pm 0.06(\text{syst.})\times 10^{-3}\text{eV}^2$ has been also obtained in Daya Bay experiment, which is comparable with Δm_{32}^2 measured in long-baseline accelerator neutrino experiment.

*The 15th International Conference on Flavor Physics & CP Violation
5-9 June 2017
Prague, Czech Republic*

¹ *Speaker, Corresponding author, E-mail: zhangqingmin@mail.xjtu.edu.cn*

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

1. Introduction of neutrino oscillation

It's predicted in the Standard Model that neutrinos should be massless. However, plenty of neutrino oscillation experiments have given a convincing evidence that neutrino have a non-zero mass. In 1998, Super-K discovered the oscillation of muon neutrinos in atmospheric neutrino observation [1]. Part of atmosphere muon neutrinos were lost during their trip though earth. Almost meanwhile, SNO and KamLAND discovered the electron neutrino oscillation in early twenty-first century[2][3].

An explanation to the loss of neutrino is neutrino oscillation theory proposed by B. Pontecorvo in 1960s. If the neutrinos have a non-zero mass and their mass eigenstates are able to be mixed with each other, the neutrino flavor will oscillate to another flavor, which means neutrinos convert to other flavors spontaneously during their flight. This is essentially a quantum interference effect. The flavor eigenstate of neutrino is superposed by the mass eigenstates with PMNS matrix [4][5][6] and the matrix can be parametrized with mixing angles θ_{12} , θ_{23} , θ_{13} and CP violation phase δ_{CP} , as shown in Eq.(1) [7].

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1)$$

Combined with the mass-squared differences Δm_{21}^2 and Δm_{31}^2 , the oscillation characteristics of neutrinos can be fully determined. The mass-squared differences determine the oscillation frequency, while the mixing angles are related to the oscillation amplitude. Precise measurements of neutrino mixing parameters are crucial to searches of CP-symmetry violation among neutral leptons and tests of neutrino oscillation theory. The recent measurement results of oscillation parameters are shown in Table 1.

Table 1 Neutrino oscillation parameters [8]

Parameter	Best fit value ($\pm 1\sigma$)
θ_{12} (degree)	$33.48^{+0.77}_{-0.74}$
θ_{13} (degree)	$8.52^{+0.20}_{-0.21}$
θ_{23} (degree)	$42.2^{+0.001}_{-0.001}$ or $49.4^{+1.6}_{-2.0}$
Δm_{21}^2 ($\times 10^{-5} \text{eV}^2$)	$7.50^{+0.19}_{-0.17}$
(normal) Δm_{31}^2 ($\times 10^{-3} \text{eV}^2$)	$2.458^{+0.046}_{-0.047}$
(inverted) Δm_{32}^2 ($\times 10^{-3} \text{eV}^2$)	$-2.448^{+0.047}_{-0.047}$
δ_{CP} (degree)	251^{+67}_{-59}

The precise measurements of θ_{12} and θ_{23} were achieved in solar neutrino and atmosphere neutrino experiment, respectively [9][10]. Nonetheless, θ_{13} , which is related to whether the ν_3 mass eigenstate is mixed with the electron neutrino state ν_e , is the last determined one [11]. The precision of neutrino mixing angle θ_{13} is of key significance in constraining the leptonic CP phase and testing neutrino oscillation theory.

2. Approaches to measure θ_{13}

There are two approaches to measure θ_{13} : One is long-baseline accelerator neutrino experiment, which is an appearance experiment; the other one is short-baseline reactor neutrino experiment, which is a disappearance experiment.

Accelerator can produce pure muon neutrino beam and these muon neutrinos will convert to electron neutrinos after a long travel in the crust. The appearance possibility of conversion $\nu_{\mu} \rightarrow \nu_e$ can be described by Eq.(2) [12].

$$P_{\nu_{\mu} \rightarrow \nu_e} = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E} \right) \quad (2)$$

The distance L between accelerator and detector is always hundreds of kilometers, which is the reason that it is usually called as long-baseline accelerator experiment. Its typical representatives are MINOS, NOvA and T2K experiments [13][14][15].

Reactor can produce pure electron anti-neutrinos via nuclear reaction and the electron anti-neutrinos will oscillate to other neutrinos flavor during its travel. Since $\Delta m_{21}^2 \ll |\Delta m_{31}^2| \approx |\Delta m_{32}^2|$ as shown in Table 1, the survival possibility of $\bar{\nu}_e$ in short-baseline reactor neutrino oscillation experiment can be described by Eq.(3) [16].

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{ee}^2 L}{4E} \right) \quad (3)$$

Where $\sin^2 \left(\frac{\Delta m_{ee}^2 L}{4E} \right) = \cos^2 \theta_{12} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) + \sin^2 \theta_{12} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E} \right)$, the distance L between reactor and detector is always shorter than 5 kilometers, which is much shorter than the accelerator experiment. Hence, it is usually called short-baseline reactor experiment. Daya bay, RENO and Double Chooz have utilized this measurement principle. In addition, Δm_{ee}^2 can also be determined precisely. Since $|\Delta m_{31}^2| \approx |\Delta m_{32}^2|$, Δm_{ee}^2 should be approximately equal to $|\Delta m_{31}^2|$ or $|\Delta m_{32}^2|$.

3. Long-baseline accelerator experiments

High energy particle accelerator is an important tool to study neutrinos, due to its advantages: high energy and good direction [17]. Two of three flavors, the muon neutrino and tau neutrino, were discovered with the help of proton accelerator [18].

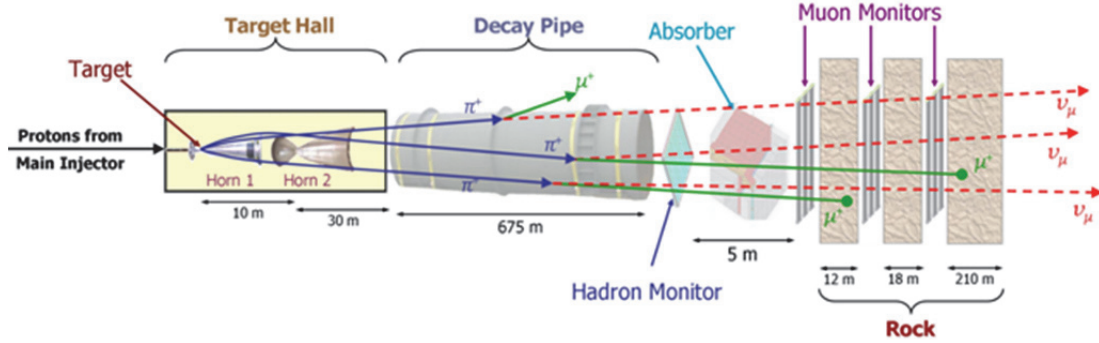


Fig. 1 Scheme of long-baseline accelerator experiment[12]

As shown in Fig.1, neutrino source is composed of proton beam, target, horn, decay pipe, and absorber[12]. The proton beam comes from an accelerator and mesons are generated during the proton's collision with target. The mesons focused by horn continue their trip in decay pipe where they will decay to neutrinos or anti-neutrinos. Then, the survived mesons and the other charged particles will be absorbed by the absorber in case of radioactivity pollution. Finally, a straight and pure muon neutrino beam has been produced. The near detector (ND) and far detector (FD) are deployed to observe the oscillation $\nu_{\mu} \rightarrow \nu_e$. The near detector is used to monitor

the un-oscillated neutrino beam spectrum and flavor content, while the far detector is used to observe the neutrino oscillation by detecting ν_e CC interaction[14]. The appearance probability can be described by Eq.(2).

T2K, MINOS and NOvA have used this measurement methods and they will be introduced below.

3.1 T2K

T2K is the first long-baseline neutrino oscillation experiment, which was designed to study neutrino oscillation via electron neutrino's appearance from muon neutrinos. One of its physical goals is to measure the last unknown mixing angle θ_{13} [13].

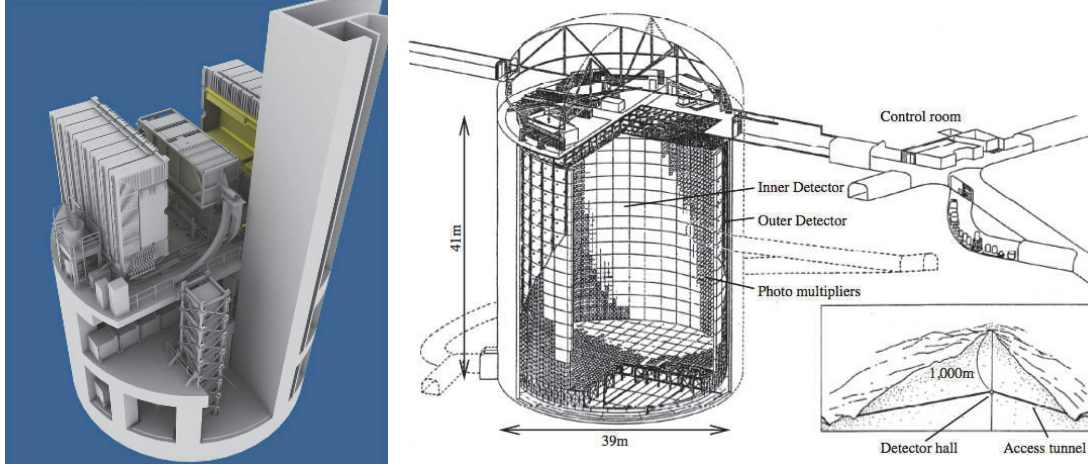


Fig. 2 Illustration of T2K near(left) and far(right) detectors[13]

The muon neutrino beam used in T2K is produced by J-PARC proton accelerator constructed in Tokai near Tokyo. The peak energy of its neutrino flux is about 0.6 GeV. Super-Kamiokande (Super-K) used as its far detector is 295 km from J-PARC and it is a water Cherenkov detector filled with 50 ktons of pure water and equipped with 13000 PMTs as shown in the right plot of Fig.2. To measure the un-oscillated neutrino spectrum as soon as it is produced, a near detector complex has been constructed at a distance of 280 meters from J-PARC and it is a magnetized offaxis tracking detector as shown in left plot of Fig.2, in which the off-axis method was adopted to generate a narrowband neutrino beam[13].

By Apr. 12th 2013, totally 6.39×10^{20} protons on target (POT) have been accumulated, giving $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ ($0.170^{+0.045}_{-0.037}$) and $\Delta m_{32}^2 = 2.51^{+0.11}_{-0.12} \times 10^{-3} \text{ eV}^2/c^4$ ($\Delta m_{31}^2 = 2.49^{+0.12}_{-0.12} \times 10^{-3} \text{ eV}^2/c^4$) for normal (inverted) mass hierarchy when $\sin^2 2\theta_{23} = 1$, $\delta_{CP} = 0$ with 28 detected events [19][20].

3.2 MINOS and NOvA

Both the Main Injector Neutrino Oscillation Search (MINOS) and the NuMI Off-axis ν_e Appearance experiment (NOvA) are located in USA. They share the NuMI neutrino beam in Fermi Lab. As shown in Fig.3, 120 GeV/c protons from the Main Injector are led to hit the carbon target. The produced mesons decay to muon neutrinos in the 675 meters long decay pipe. To identify the beam, the near detectors are built near NuMI. The far detectors of both experiments are built at a distance of hundreds of kilometers to measure the ν_e event rate.

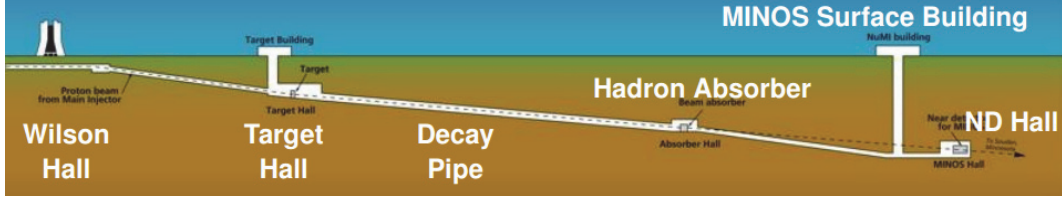


Fig. 3 Deployment of MINOS experiment [12][19]

MINOS detectors are deployed along the NuMI baseline, which can achieve a wide energy spectrum to help measuring the oscillation frequency, while the NOvA detectors are off-axis with an off-axis angle of 14 mrad, which helps to concentrate the neutrino energy in visible range of 1~3 GeV to reduce neutral current backgrounds. Their common beam source and detectors are summarized in Table 2 [12][14] [21].

Table 2 Summary of MINOS and NovA experiments

	MINOS	NOvA
Neutrino Beam	NuMI at Fermi	
Near Detector	282 steel / 153 scintillator planes 1 km from target	206 layers / 96 cells of PVC lattice filled with liquid scintillator 1km from target
Far Detector	484 steel / scintillator planes at 735km from target	928 layers / 384 cells of PVC lattice filled with liquid scintillator at 810 km from target
Background	Neutral Current (NC), ν_μ Charged Current (CC), beam ν_e Charged Current, ν_τ Charged Current	
Selection of candidate events	Reconstructed energy from 1 to 8 GeV with at least 5 hit planes in a row and one reconstructed shower	Total calorimetric energy of 1.3~2.7 GeV with additional requirements on occupied cell and length of particle path

With a exposure of 7.25×10^{20} POTs for MINOS and 3.45×10^{20} POTs for NOvA, the measurement results of θ_{13} has been obtained for normal and inverted mass hierarchies as shown in Table 3 ($\sin^2 2\theta_{23} = 1$, $\delta_{CP} = 0$)[14][15][22][23].

 Table 3 $\sin^2 2\theta_{13}$ and Δm_{32}^2 Measurement in MINOS and NovA

Experiment		MINOS	NOvA
$\sin^2 2\theta_{13}$	NH	<0.12	<0.2
	IH	<0.2	<0.3
Δm_{32}^2 ($\times 10^{-3} \text{ eV}^2$)	NH	2.37 ± 0.09	2.67 ± 0.11
	IH	-2.425 ± 0.105	-2.72 ± 0.11

4. Short-baseline reactor experiments

The nuclear reactor plant can produce a huge number of low-energy electron anti-neutrinos. Eq. (1) shows the survival probability of electron antineutrino $\bar{\nu}_e$ is a function of E/L [11].

In order to reduce the reactor-related errors, the experiments are equipped with near and far detectors for relative measurements. The near detectors are used to monitor the reactor electron anti-neutrino flux, while the far detectors are deployed at a distance of 1 or 2 km from the reactors to detect the oscillation of neutrinos near the first maximum point [11][24][25].

The neutrinos are detected via the inverse beta decay reaction (IBD) with protons in the sensitive liquid scintillator (LS). A neutron and a positron are generated during IBD. The positron annihilates with electron rapidly, giving a prompt signal, while the neutron is captured by nuclei (Gd, H etc.) when it became a thermal neutron, giving a delayed signal. The selection of neutrino events is based on the coincidence in time and energy [24][26][27]. Identical detectors are used in near and far sites to reduce the detector-related errors. Considering the ratios of target mass, baseline, detection efficiency and survival probability at near and far sites, the θ_{13} and Δm_{ee}^2 can be obtained.

The current best measurements of θ_{13} come from the reactor electron anti-neutrino oscillation experiments Daya Bay [11], RENO [24] and Double Chooz [28], in which Daya Bay is the most accurate one.

4.1 Daya Bay

There are three experimental halls (EHs) in Daya Bay experiment which is near the Daya Bay nuclear power plant complex. As shown in Fig. 4, the complex has 3 sets of reactor cores. Their thermal power is 17.4 GW in total [26]. Eight three-zones modular antineutrino detectors (AD) are installed with two ADs at each near site (EH1 and EH2), and four ADs in the far site (EH3) [11].

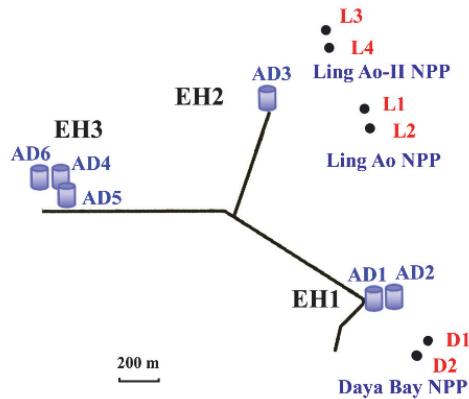


Fig. 4 Layout of Daya Bay experiment [24] [26]

All the detectors are deployed underground with rock overburden to suppress the backgrounds from cosmic-rays. ADs are surrounded with ultra-pure water pools which can shield the ambient radiation and serve as Cherenkov detectors using photomultiplier tubes (PMTs) to reduce muon-induced backgrounds. In addition, an array detector made of resistive plate chambers is located above the water pool and independently detects muons [29][30]. As shown in Fig. 5, the central target region of each AD is filled with 20 ton Gd-doped liquid scintillator. The inner acrylic vessel is 3.1 meter in diameter, which is surrounded by the pure liquid scintillator in outer acrylic vessel and mineral oil in a stainless steel vessel. Scintillation photons are detected by 192 8-inch PMTs, which are equally divided into 8 rings and mounted on the inner cylindrical surface of each stainless steel vessel.

The Daya Bay reactor neutrino experiment is the first experiment to exclude a nonzero value of θ_{13} with a significance of more than 5 standard deviations in 7 March 2012. As shown in Fig. 6, the latest result $\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(\text{stat.}) \pm 0.0019(\text{syst.})$ from Daya Bay experiment is given by analyzing the rates and positron energy spectra of the total observed 2.5

$\times 10^6$ electron antineutrino inverse beta-decay interactions in the far and near detectors. Consequently, the effective neutrino mass-squared difference of $|\Delta m_{ee}^2| = 2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.}) \times 10^{-3} \text{eV}^2$ has been also obtained [11], which is comparable with Δm_{32}^2 measured in long-baseline accelerator neutrino experiment.

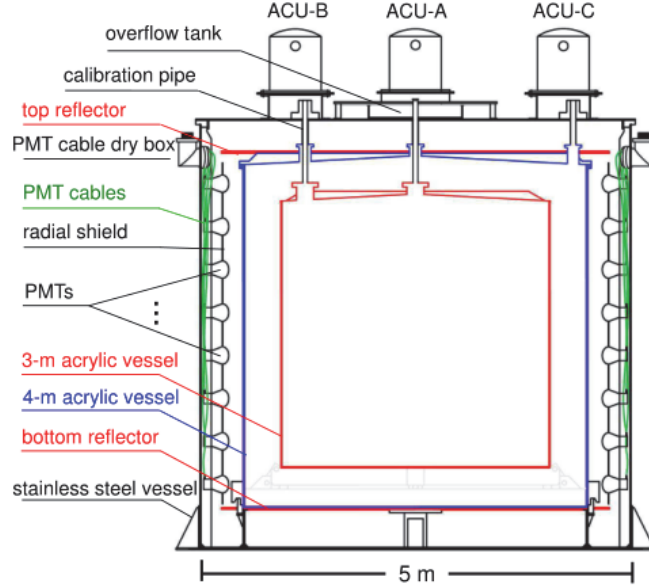


Fig. 5 Day Bay detector structure[11]

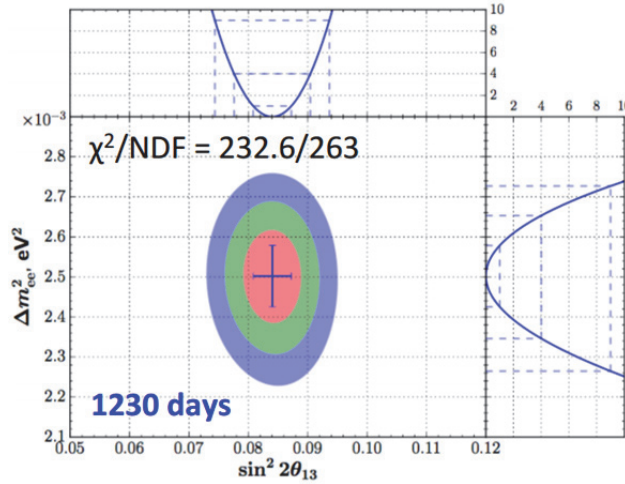


Fig. 6 Confidence regions of $\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ from Daya Bay [11]

4.2 RENO

RENO is constructed at Jeollanam-do in Korea utilizing the neutrinos produced by YongGwang nuclear power plant with a thermal power of 16.8 GW. Two identical anti-neutrino detectors with 16 tons of targets are located at 294 m and 1383 m from the nuclear power plant array. To reduce the affect of cosmic ray, the far and near detector are under 450 and 120 meters of water equivalent rock overburden[24].

As shown in Fig.7, each RENO AD is similar to that of Daya Bay except the dimensions, PMT size and number of PMTs. Additionally, RENO only uses ultra-pure water pools to shield

the ambient radiation and to serve as Cherenkov detectors to reduce muon-induced backgrounds. For details, please see the reference [31].

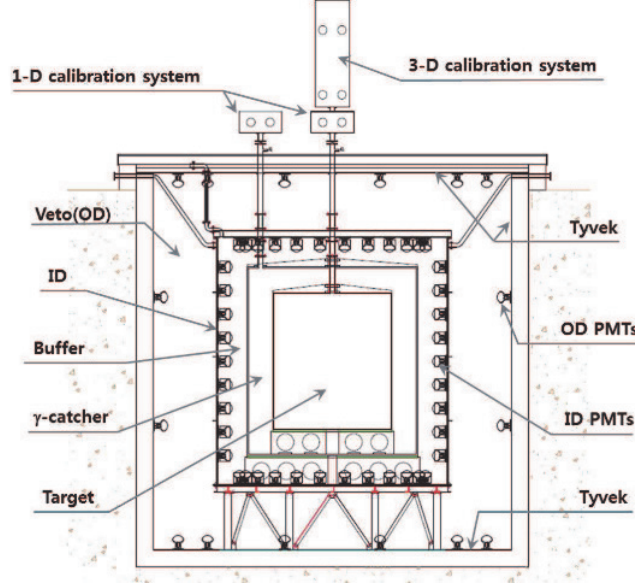


Fig. 7 RENO AD structure[31]

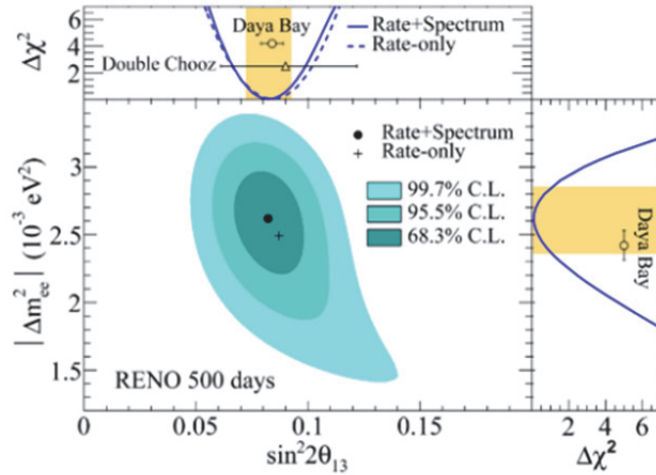


Fig. 8 Confidence regions of $\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ from RENO [24]

A clear baseline dependent disappearance of $\bar{\nu}_e$ is observed in the deficit of the observed number of $\bar{\nu}_e$. As shown in Fig.8, RENO released its latest measurement results of $\sin^2 2\theta_{13}$ and the effective neutrino mass-squared difference of $|\Delta m_{ee}^2|$ as shown below [24].

$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(stat.) \pm 0.006(syst.)$$

$$|\Delta m_{ee}^2| = [2.62^{+0.21}_{-0.23}(stat.)^{+0.12}_{-0.13}(syst.)] \times 10^{-3} eV^2$$

4.3 Double Chooz

The Double Chooz is located at Ardennes in France. Two reactor cores in the Chooz Nuclear Power Plant are utilized as the neutrino source, giving a total thermal power of 8.54 GW. Each detector has 8.3 tons of targets and two detectors located underground at 400 m and 1050 m from the power plant, respectively. Each Double Chooz AD is similar to that of Daya Bay except the dimensions, PMT size and number of PMTs. Double Chooz has two veto

detectors made of scintillator and uses steel for shielding, which is different from the other two experiments. For details, please see Fig.9 [27][28].

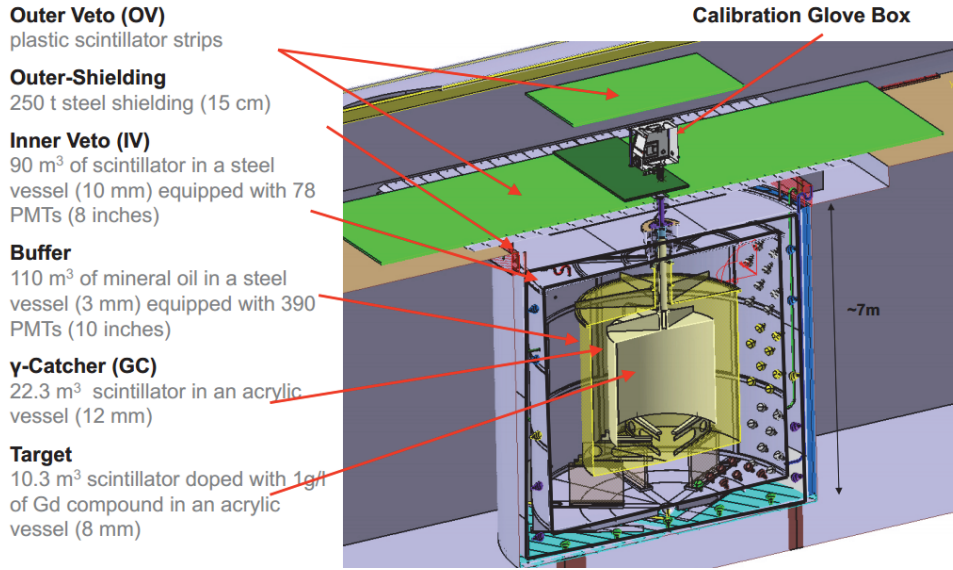


Fig. 9 Double Chooz AD structure

The far detector of Double Chooz has worked since 2011, while the near detector started to take data in 2014. With the analysis of data from far detector, Double chooz released its latest measurement result of $\sin^2 2\theta_{13} = 0.088 \pm 0.030$ [28].

5.Summary and prospect

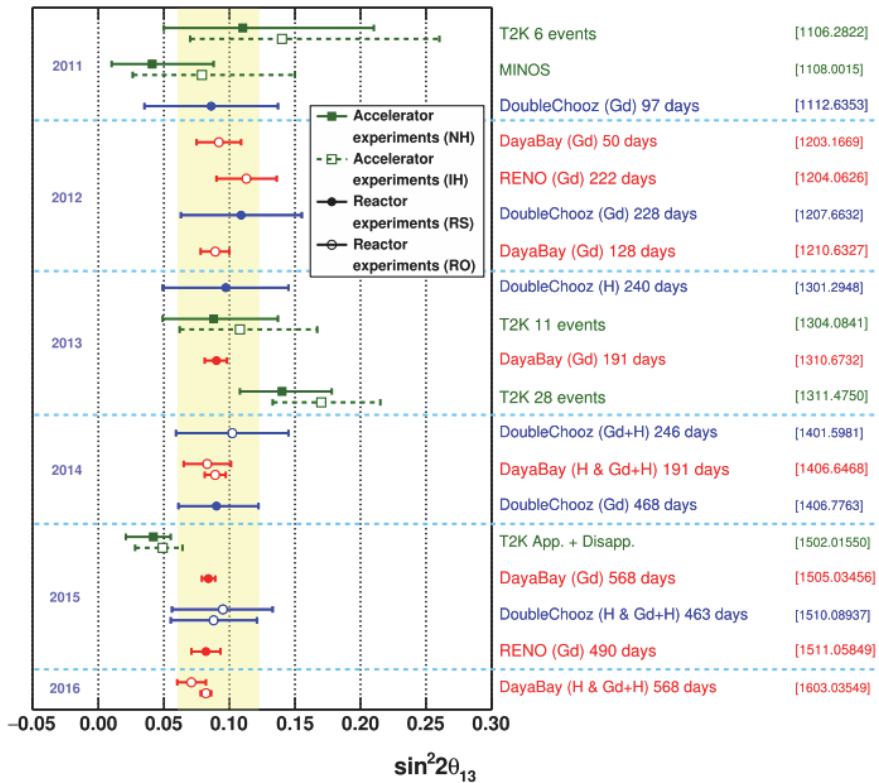


Fig. 10 Evolution of θ_{13} measurement[25]

The precise measurement of θ_{13} is of key significance in constraining the leptonic CP phase and very critical for validation of neutrino oscillation theory. Two kinds of experiments, long-baseline accelerator neutrino experiment and short-baseline reactor neutrino experiments, have been carried out to measure it precisely. Its measurement evolution history is shown in Fig. 10. Daya Bay is the first experiment to exclude $\theta_{13}=0$ with a significance of more than 5 standard deviations and has given the most accurate measurement of $\sin^2 2\theta_{13} = 0.0841 \pm 0.0027$ (stat.) ± 0.0019 (syst.). In the same time, the effective neutrino mass-squared difference of $|\Delta m_{ee}^2| = 2.50 \pm 0.06$ (stat.) ± 0.06 (syst.) $\times 10^{-3} \text{eV}^2$ has been also obtained in Daya Bay experiment and the result is comparable with Δm_{32}^2 in long-baseline accelerator neutrino experiment.

After the discovery of a surprisingly large value of θ_{13} , there are still two oscillation parameters to be determined: Mass Hierarchy and CP phase. Non-zero and large θ_{13} discovery opens a door to neutrino Mass Hierarchy. Several experiments, including the JUNO in China[7][8], DUNE in USA and the Hyper-K in Japan[8], will be constructed to do the further explorations, which will open a new door to a new particle physics.

Reference

- [1] Nakamura K., Atmospheric neutrino results from Super-Kamiokande[J], Nuclear Physics B - Proceedings Supplements, 1998, 66(1–3):282-289.
- [2] McDonald A B, Ahmad Q R, Allen R C, et al., Direct Evidence for Neutrino Flavor Transformation from Neutral current Interactions in SNO [J], Physical Review Letters, 2002, 646(1):3164.
- [3] Eguchi K, Enomoto S, Furuno K, et al., First results from KamLAND: evidence for reactor antineutrino disappearance.[J], Physical Review Letters, 2003, 90(2):021802.
- [4] Pontecorvo B., Mesonium and Antimesonium[J], Soviet Phys JETP, 1957, 6(2):429-431.
- [5] Pontecorvo B., Neutrino Experiments and the Problem of Conservation of Leptonic Charge[J], Journal of Experimental & Theoretical Physics, 1981, 26(5):984.
- [6] Maki Z, Nakagawa M, Sakata S., Remarks on the Unified Model of Elementary Particles[J], Progress of Theoretical Physics, 1962, 28(5):870-880.
- [7] Cao J., Daya Bay and Jiangmen Underground Neutrino Observatory (JUNO) neutrino experiments (in Chinese), Sci Sin-Phys Mech Astron, 2014, 44: 1025–1040, doi: 10.1360/SSPMA2014-00174
- [8] Qian X, Vogel P., Neutrino mass hierarchy [J], Progress in Particle & Nuclear Physics, 2015, 83:1-30.
- [9] Nakamura K., Atmospheric neutrino results from Super-Kamiokande[J], Nuclear Physics B - Proceedings Supplements, 1998, 66(1–3):282-289.
- [10] Abe S, Ebihara T, Enomoto S, et al., Precision measurement of neutrino oscillation parameters with KamLAND.[J], Physical Review Letters, 2008, 100(22):221803.
- [11] An F P, Balantekin A B, Band H R, et al., Measurement of electron antineutrino oscillation based on 1230 days of operation of the Daya Bay experiment[J], Phys.Rev.D, 2017, 95(7).
- [12] Lisa Whitehead, New Results for Muon Neutrino to electron Neutrino Oscillations in the MINOS Experiment [R], Madison, Daya Bay Analysis Workshop, 2010
- [13] K. Abe et al., The T2K Experiment[J], Nucl. Instr. and Meth. A 659 (1) (2011) 106-135

- [14] Adamson P, Andreopoulos C, Armstrong R, et al., Measurement of the neutrino mass splitting and flavor mixing by MINOS.[J], Physical Review Letters, 2011, 106(18):181801.
- [15] Adamson P, Ader C, Andrews M, et al., First Measurement of Electron Neutrino Appearance in NOvA[J], Physical Review Letters, 2016, 116(15):151806.
- [16] An F P, A.B. Balantekin, Band H R, et al., Spectral measurement of electron antineutrino oscillation amplitude and frequency at Daya Bay[J], Physical Review Letters, 2014, 112:061801
- [17] Huber P, Lindner M, Rolinec M, et al. Prospects of accelerator and reactor neutrino oscillation experiments for the coming ten years[J]. Phys.rev.d, 2004, 70(7):357-363.
- [18] Cao J., History and Future of Neutrino Investigation(in Chinese) [J], Modern Physics, 2015(6):4-8.
- [19] Michael Wilking, New Results from the T2K Experiment [R], EPS Conference, 2013.
- [20] Petrov Y, Collaboration K., Summary of the Latest Results and Future Prospects from the T2K Experiment[C], 4th Symposium on Prospects in the Physics of Discrete Symmetries, Journal of Physics: Conference Series 631 (2015) 012055.
- [21] Patterson R B., The NOvA experiment: status and outlook[J], Nuclear Physics B, 2013, 235-236(s 235–236):151-157.
- [22] Adamson P, Anghel I, Aurisano A, et al., Combined analysis of $\nu\mu$ disappearance and $\nu\mu \rightarrow \nu e$ appearance in MINOS using accelerator and atmospheric neutrinos.[J], Physical Review Letters, 2014, 112(19):191801.
- [23] Adamson P, Aliaga L, Ambrose D, et al., Measurement of the Neutrino Mixing Angle θ_{23} in NOvA[J], Phys.rev.lett, 2017, 118(15):151802.
- [24] J. H. Choi, W. Q. Choi, et al., Observation of Energy and Baseline Dependent Reactor Antineutrino Disappearance in the RENO Experiment[J], Physical Review Letters, 2015, 116(21):211801.
- [25] Suekane F., Double Chooz and a history of reactor θ_{13} experiments[J], Nuclear Physics, 2016, 908:74-93.
- [26] Ling J., Daya Bay Reactor Antineutrino Experiment [J], Physics Procedia, 2015, 61(2):323-330.
- [27] Abe Y, Aberle C, Anjos J C D, et al., First Measurement of θ_{13} from Delayed Neutron Capture on Hydrogen in the Double Chooz Experiment[J], Physics Letters B, 2013, 723(1-3):66-70.
- [28] Kaneda M., Results from the Double Chooz experiment[J], 2016, 126:04023.
- [29] Q. Zhang et al., Offline software of RPC detector system in Daya Bay Reactor Neutrino Experiment, J. Phys. Conf. Ser. 396 (2012) 022061.
- [30] Z. Ning et al., Calibration algorithms of RPC detectors at Daya Bay neutrino experiment, 2013 JINST 8 T03007.
- [31] Ahn J K, Chebotaryov S, Choi J H, et al., Observation of reactor electron antineutrinos disappearance in the RENO experiment.[J], Physical Review Letters, 2012, 108(19):269-273.