Study of neutrino oscillations in accelerator experiments

Yu. G. Kudenko[a*]

[a] *Institute for Nuclear Research of the Russian Academy of Sciences*
60 October Revolution Pr. 7A, 117312 Moscow, Russia

Abstract

The recent results and current status of neutrino oscillation study in long baseline and short baseline accelerator experiments are presented.

1 Inroduction

In recent years, the atmospheric [1], solar [2], reactor [3], and accelerator [4, 5, 6] experiments have provided convincing evidence of neutrino oscillations and therefore have proved that neutrinos have non–zero masses. This phenomenon is the first clear example of new physics beyond the Standard Model. Three generation neutrino oscillations are described by six independent parameters: three mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$, two mass-squared differences $\Delta m^2_{12} = m^2_2 - m^2_1$ and $\Delta m^2_{23} = m^2_3 - m^2_2$, and one complex phase δ. Both mass differences and two mixing angles (θ_{12} and θ_{23}) are measured. The mixing angle θ_{13} was found to be small and only an upper limit was obtained [7]. Presently nothing is known about the CP violating Dirac phase δ. The near–future neutrino oscillation experiments will be focused on the measurements of the unknown neutrino parameters: θ_{13}, mass hierarchy, and δ. Another important goal of these experiments is to measure the known mixing parameters more precisely. This review is focused on the study of neutrino oscillations in accelerator experiments. The most interesting results obtained by now, the present status of running experiments and near future plans are presented.

To discuss the basic features of oscillation experiments we consider the main oscillation formulas using the three-generation framework. The approximate probabilities for neutrino oscillations can be wrtten as follows:

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Big(\frac{1.27\Delta m^2_{23}(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}\Big), \tag{1}$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2\Big(\frac{1.27\Delta m^2_{23}(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}\Big), \tag{2}$$

where L is the distance from the neutrino source and E is the neutrino energy.

There are two types of oscillation measurements: "disappearance" and "appearance" experiments. A "disappearance" experiment measures a deficit in the expected neutrino flux that requires a set–up with a near and a far detector. The near detector (located close to the production target) measures the parameters of the neutrino beam prior to oscillation. Such a method is used for prediction of the unoscillated event rate and neutrino spectrum at the far detector. Then, the measured deficit and distortion of the neutrino spectrum are used for

*e-mail: kudenko@inr.ru

extraction of oscillation parameters. From Eq. (2) one can see that the maximum sensitivity to the oscillation phase, and correspondingly to Δm^2_{23}, is obtained when $E/L \approx \Delta m^2_{23}$. "Appearance" experiments search for transitions $\nu_\mu \to \nu_e$, as seen from Eq. (1), by measurement of interactions of neutrino type ν_e in the far detector.

2 K2K

The KEK to Kamioka long-baseline neutrino oscillation experiment (K2K) [4] was the first accelerator experiment to measure the neutrino oscillation in the same Δm^2 region as atmospheric neutrinos. A nearly pure ν_μ beam with a mean energy of 1.3 GeV was produced with the 12 GeV KEK proton synchrotron. The neutrino energy spectrum and flux at KEK were measured by a near neutrino detector complex (an 1 kt water Cherenkov detector and a fine grained detector system) located 300 m from the production target. The far detector was Super-Kamiokande (SK), a 50 kt water Cherenkov detector, located 250 km from KEK. K2K took data from June 1999 to November 2004 with $\sim 10^{20}$ protons on target (POT).

Super-Kamiokande detected 112 neutrino events in its fiducial volume with an expectation of $158.1^{+9.2}_{-8.6}$ events without oscillation. The spectrum distortion expected from oscillation is also seen in 58 single-ring muon-like events which have had their energy reconstructed as shown in Fig. 1. A combined analysis of the flux and spectrum excluded the null hypothesis of no

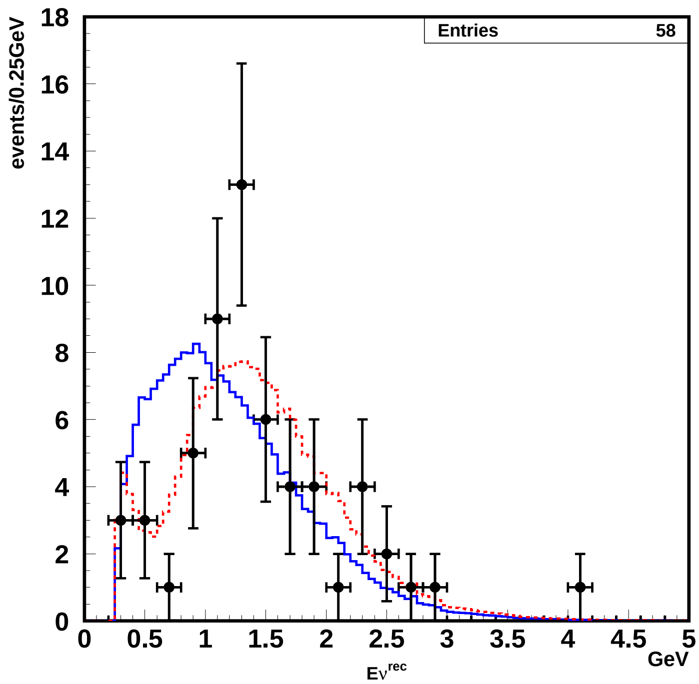

Figure 1: The reconstructed E_ν distribution for 58 one-ring $\mu-$like events observed in K2K. The dashed line is the best fit spectrum with neutrino oscillation and the solid line is the expectation without oscillation.

oscillation at the 4.3σ level [5]. In a two flavor oscillation scenario, the best fit oscillation parameters of $\Delta m^2 = 2.8 \times 10^{-3}$ and $\sin^2 2\theta = 1$ were obtained. These results are consistent with neutrino oscillation parameters previously measured by Super-Kamiokande using atmospheric neutrinos. Thus, the first LBL neutrino experiment K2K confirmed the neutrino oscillation result obtained by SK and opened a new era for precision measurements of oscillation parameters in long baseline experiments.

3 MINOS

The Main Injector Neutrino Oscillation Search (MINOS) experiment uses the NUMI beam which is produced by 120 GeV protons from the Main Injector at FNAL. The ν_μ beam is measured at the Near Detector (ND) with a 29t fiducial mass located at 1 km from production target and at the Far Detector (FD) with a 4kt fiducial mass located 735 km away in the Soudan Underground Mine, Minnesota. The oscillation parameters are extracted by comparing the reconstructed ν_μ spectra at the ND and FD. Both detectors are magnetized steel–scintillator tracking calorimeters, composed of planes of 2.54 cm thick steel and 1.0 cm thick scintillator with an average toroidal magnetic field of about 1.3 T.

Neutrino flavor can be identified in charged current interactions by the event topology produced by the associated charged lepton. Muons deposit energy in successive detector planes forming a long track, while electrons deposit energy in a relatively narrow and short region that corresponds to an electromagnetic shower. MINOS begun collecting NUMI beam data in 2005 and accumulated about 7.2×10^{20} POT by Summer 2010. From all runs 1986 ν_μ events were observed while 2451 events were expected without oscillations. The oscillation parameter values of $\Delta m^2_{23} = (2.35^{+0.11}_{-0.08}) \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} > 0.91$ (90% CL) were obtained. The uncertainties include both the statistical error and the systematic error. The reported value of Δm^2_{23} is the most precise measurement of this parameter. New MINOS result (reported at Neutrino2010 [8]) is shown in Fig. 2 along with the recent result of SuperKamiokande.

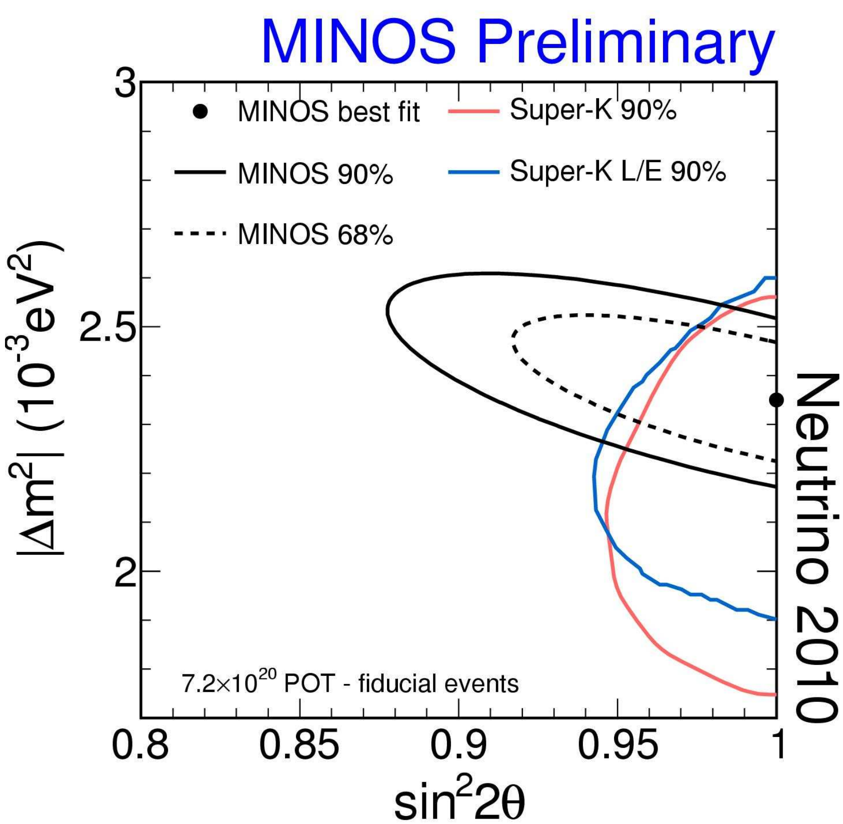

Figure 2: Confidence interval contours obtained for the hypothesis of two–flavor oscillations for 7.2×10^{20} POT. The best fit point is $\Delta m^2_{23} = (2.35^{+0.11}_{-0.08}) \times 10^{-3}$ and $\sin^2 2\theta_{23} = 1.00$

MINOS also accumutaled statistics with antineutrino beam for 1.71×10^{20} POT [8]. As a result, 97 antineutrino events were detected in Far Detector and 155 events were expected in the absence of antineutrino disappearance. These data disfavour no oscillations at the 6.3σ level. It was obtained for antineutrino that $\Delta m^2_{23} = (3.36^{+0.45}_{-0.40}(\text{stat.}) \pm 0.06(\text{syst.})) \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 0.86 \pm 0.11(\text{stat.}) \pm 0.01(\text{syst.})$. Confidence interval contours for antineutrino and neutrino data are presented in Fig 3. There is some hint that $P(\nu_\mu \rightarrow \nu_\mu$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

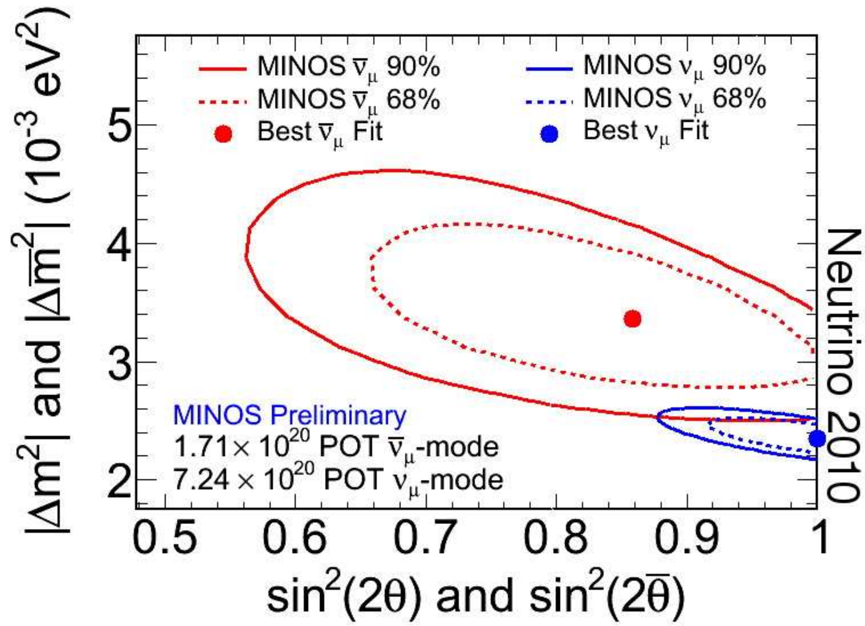

Figure 3: Confidence interval contours and central values of mixing parameters obtained by MINOS for antineutrino and neutrino data.

are not the same, since a difference of about 2.2σ is obtained for Δm^2_{23} for ν_μ and $\bar{\nu}_\mu$, but more statistics and more detailed study of systematics are needed to make more solide statement. Moreover, it is interesting to note that measurements by SuperKamiokande did not find any difference in Δm^2_{23} and $\Delta \bar{m}^2_{23}$ [9].

MINOS also reported a new search for $\nu_\mu \rightarrow \nu_e$ transitions based on 7×10^{20} POT exposure [10]. It was observed 54 candidate ν_e events in the Far Detector with a background $49.1 \pm 7.0(\text{stat}) \pm 2.7(\text{syst})$ events predicted by the measurements in the Near Detector. The upper limit on the probability of $\nu_\mu \rightarrow \nu_e$ oscillations gives $2\sin^2 2\theta_{13} \sin^2\theta_{23} < 0.12(0.20)$ at the 90% CL at $\delta = 0$ for the normal (inverted) hierarchy. This limit obtained for all values δ in a direct measurement of $\nu_\mu \rightarrow \nu_e$ is slightly better than the CHOOZ result.

4 OPERA

The OPERA experiment [11] is designed to directly observe the $\nu_\mu \rightarrow \nu_\tau$ oscillation appearance mode through the decays of τ leptons produced in ν_τ CC interactions. A wide band muon neutrino beam with an average energy of about 17 GeV was produced at the 400 GeV CERN SPS and directed to a neutrino detector installed in the underground Gran Sasso Laboratory 736 km away from the neutrino source. The $\bar{\nu}_\mu$ contamination in the neutrino beam is about 4%, the ν_e and $\bar{\nu}_e$ contaminations are less than 1%, and the fraction of ν_τ from D meson decays is $\sim 10^{-6}$. In this experiment, the neutrino beam was optimized to overcome the kinematic threshold for τ production and to detect τ decay products at the Gran Sasso while the L/E_ν is far from the atmospheric neutrino oscillation maximum. The OPERA detector consists of two identical Super Modules each of which has a target section of about 900 t of lead/emulsion film modules (bricks), a scintillator tracker detector, and a muon spectrometer. The short lived τ lepton ($c\tau = 87.11\mu$m) is identified through its decay topologies which require an accuracy

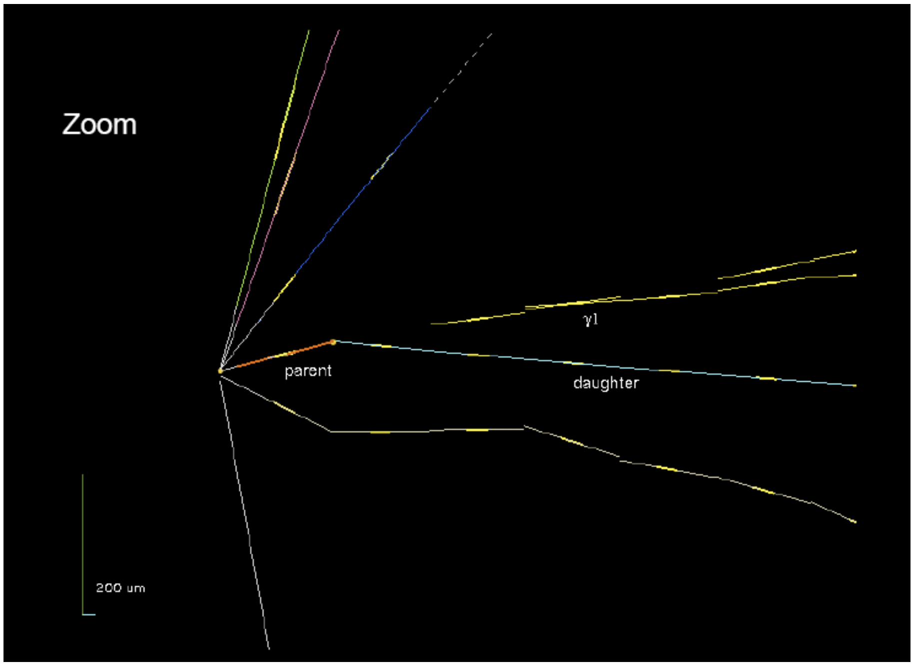

Figure 4: Display of the first $\tau-$candidate event detected by OPERA.

of about 1 μm and a few mrad for position and angular measurements, respectively. There are two classes of τ decays inside the bricks: short (τ decays in the same lead plate where ν interaction occurred) and long (τ decays in the first or second downstream lead plate) decays. The τ identification is based on a multi prong deep inelastic scattering (short decays) and on a detection of a 'kink' between the τ and daughter track for both deep inelastic and quasi elastic neutrino interactions. It is expected that the τ detection efficiency will be about 10%. Experiment started data taking in 2007 and accumulated about 4.2×10^{19} POT by 2010. The first candidate for ν_τ was found after the analysis of about 35% of accumulated data [12]. The enlarged topology of this events is shown in Fig 4. The event is most probably the decay $\tau^- \longrightarrow h^-, n\pi^0, \nu_\tau$. The observation of the candidate for ν_τ has a significance of 2.36σ of not being a background fluctuation. The expected number of ν_τ events detected in the analysed sample is 0.54 ± 0.13. OPERA continues data taking and expects 5–10 ν_τ events by the experiment completion.

5 MiniBooNE

The primary goal of the Mini Booster Neutrino Experiment (MiniBooNE) [14] is to test the LSND result (indication for $\bar{\nu_\mu} \rightarrow \bar{\nu_e}$ oscillation reported by with $\Delta m^2 \sim 1.0$ eV^2 [13]) in an unambiguous and independent way. MiniBooNe uses the Fermilab Booster neutrino beam, which is produced from 8 GeV protons incident on a beryllium target located inside a focusing horn which focuses charged pions and kaons which then decay in a 50 m long tunnel. The ν_μ energy spectrum peaks at 700 MeV and extends to approximately 3000 MeV, with a small component of ν_e from three–body decays of muons and kaons. The detector location was chosen to optimize the sensitivity to oscilation parameter $\Delta m^2 \sim 1$eV similar to that of LSND with L(m)/E(MeV) ~ 1. The MiniBooNE detector, a spherical tank of inner radius 610 cm filled with 800 tons of pure mineral oil, CH_2, is located 541 m from the target. Charged particles can emit both prompt directional Cherenkov light and delayed isotropic scintillation light. The detector is instrumented on its outer surface with 1280 inward-facing 8–inch PMTs providing about 10% photocathode coverage. Neutrino interactions within the fiducial volume are identified via the

Cherenkov radiation produced by the charged particles emerging from the interaction. Using the pattern and timing of the Cherenkov and scintillating light hitting the PMT's electrons can be distinguished from other particles (muons and neutral pions). The signature of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is an excess of ν_e and $\bar{\nu}_e$ induced charged currect quasielastic events. It should be noted that MiniBooNe has no near detector which could measure the netrino flux before oscillations and could cancel many systematics uncertanties using a Far/Near ratio. To provide the nesessary sensitivity, the experiment completely relies on Monte-Carlo simulations which include the production and decays of hadrons, the beam line and detector geometry, neutrino cross sections and other factors.

The result with neutrino beam obtained for integral intensity of 6.58×10^{20} protons on target is shown in Fig. 5 The energy distribution of the ν_e candidate events is shown in Fig. 5 (top).

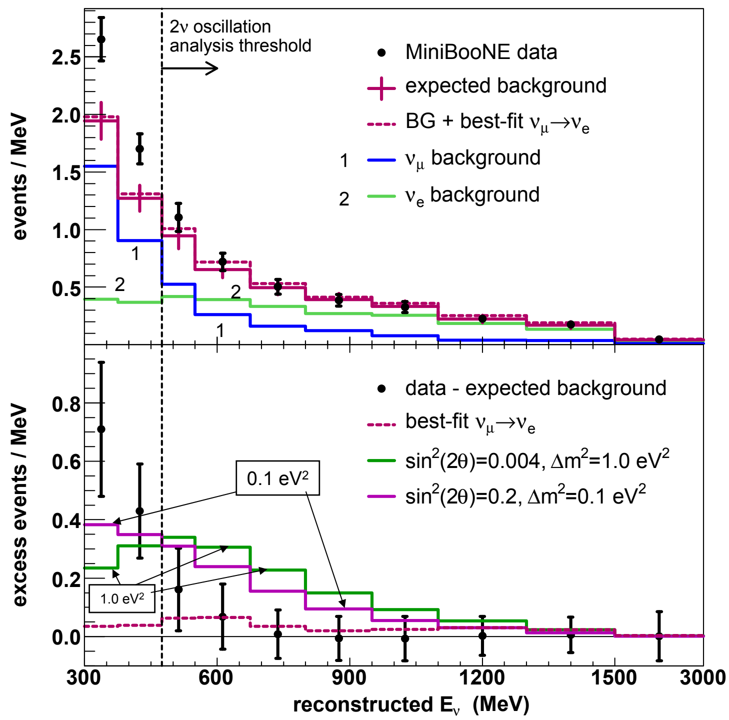

Figure 5: Top: the observed neutrino energy distribution for selected ν_e CCQE candidate events. The points show the experimental data with statistical errors. The histogram is the expected background. Also shown are the best–fit oscillation spectrum (dashed histogram) and the background contributions from ν_μ and ν_e events. Bottom: the distribution of the excess of ν_e CCQE candidate events after subtraction of the predicted background, where the points represent the data with total errors and the two histograms correspond to LSND solutions with high and low Δm^2. The vertical dashed line shows the energy threshold used in the two–neutrino oscillation analysis.

In the oscillation analysis region 475 MeV $< E_\nu^{\mathrm{QE}} <$ 3000 MeV, 380 events were observed. The expected background was estimated to be $355 \pm 19(\mathrm{stat.}) \pm 35(\mathrm{syst.})$ events. No significant excess of events over background ($22 \pm 19 \pm 35$) was found, and therefore no evidence for neutrino oscillations was found. MiniBooNE excluded two neutrino appearance only oscillations as the explanation of the LSND anomaly at the 98% confidence level [14]. It should be noted that MiniBooNE observed a significant excess of events ($96 \pm 19 \pm 21$) in the neutrino energy interval 300–475 MeV [15].

MiniBooNe also accumulated statistics with antineutrino beam for 5.66×10^{20} POT. An excess of 20.9 ± 14.0 $\bar{\nu}_e$ events in the oscillation region above 475 MeV was observed [16].

According to the MinibooNe analysis, the probability that this excess can be consistent with the expected background is 0.5%. The MiniBooNe conclusion: the results is consitent with $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with the 0.1 to 1.0 eV^2 Δm^2 range and consistent with the LSND result. An excess of 12 event was also found for a low energy interval 200–475 MeV. The experiment is planning to double statistics in antineutrino mode. However, it seems that it will not be able to provide any decisive conclusion on oscillations with $\Delta m^2 \sim 01. - 1.0$ eV^2 and unambiguously test the LSND result.

6 T2K

The T2K (Tokai–to–Kamioka) experiment [17] uses a high intensity off–axis neutrino beam produced by a 30 GeV proton beam at JPARC (Japan Proton Accelerator Research Complex), SuperKamiokande as a far neutrino detector, and a set of dedicated neutrino detectors located at a distance of 280 m from the pion production target to measure the parameters of the unoscillated neutrino beam. The first phase of the T2K experiment pursues two main goals: a sensitive measurement of θ_{13} and a more accurate determination of the parameters $\sin^2 2\theta_{23}$ and Δm^2_{23} than any previous experiment.

As follows from Eq. (1), the maximum sensitivity to $\nu_\mu \to \nu_e$ transition is expected around the oscillation maximum for $\nu_\mu \to \nu_\tau$. T2K will adopt the off–axis beam configuration in which the neutrino energy is almost independent on the pion energy and quasi-monochromatic neutrino spectrum can be obtained. The neutrino beam has an angle of 2.5 degrees with respect to the beam axis providing a narrow neutrino spectrum with mean neutrino energy of about 0.6 GeV, as shown in Fig. 6. The neutrino peak energy is tuned to maximize the sensitivity

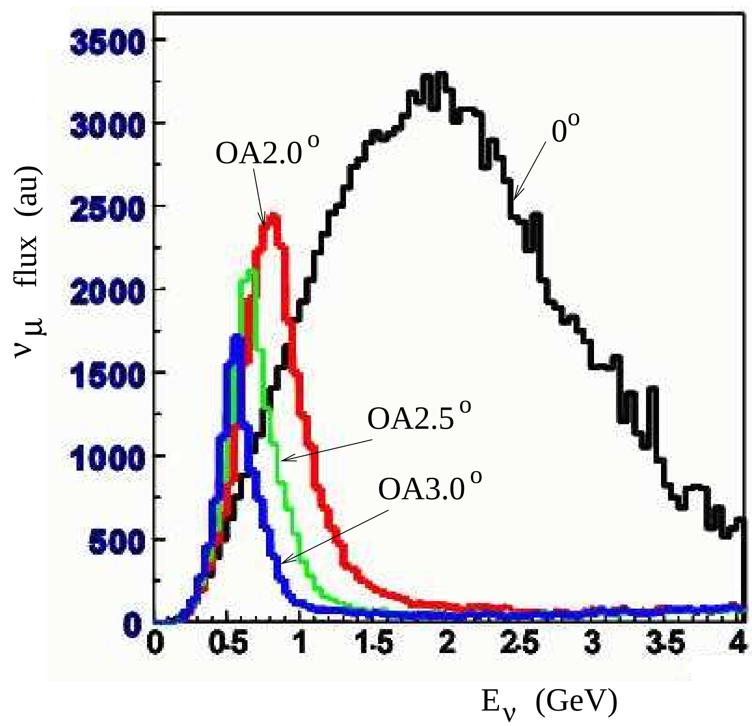

Figure 6: Neutrino energy spectra at 0° and different off–axis angles.

to neutrino oscillation with atmospheric parameters for a given baseline of 295 km. The high energy tail is considerably reduced with respect to the standard on–axis wide–band beam. This allows to minimize the neutral current π^0 background in the ν_e appearance search. Moreover, the intrinsic contamination of ν_e's from muon and kaon decays is expected to be about 0.5% around the peak energy.

To achieve the T2K goals, precise measurements of the neutrino flux, spectrum and interaction cross sections are needed. For these purposes, the near detector complex (ND280) is constructed at a distance of 280 m from the target along the line between the average pion decay point and SK. This complex has two detectors: an on–axis detector consisting of 7×7 iron–scintillator stacks formed in a cross–configuration (neutrino monitor) to provide the measurement of the neutrino beam intensity and direction, and an off–axis detector which consists of the UA1 magnet operated with a magnetic field of 0.2 T, a Pi-Zero detector (POD), a tracking detector which includes time projection chambers and fine grained scintillator detectors (FGD's), an electromagnetic calorimeter, and a side muon range detector. Detailed description of this detector can be found in Ref. [18].

The search for the ν_e appearance will be performed by looking for single ring electron-like events in the SK detector due to the charged current quasi-elastic scattering, $\nu_e + n \to p + e^-$. The SK efficiency for detection of ν_e's through such a process is expected to be about 40% while the π^0 background is suppressed by a factor of 100. If $\sin^2 2\theta_{13} \sim 0.1$, i.e. close to the present limit, about 100 oscillated ν_e's will be detected by SK with ~ 20 background events from ν_μ's (mainly π^0's from charged and neutral currents) and beam ν_e's.

Fig. 7 shows the 90% C.L. sensitivity to the ν_e appearance as a function of POT. The

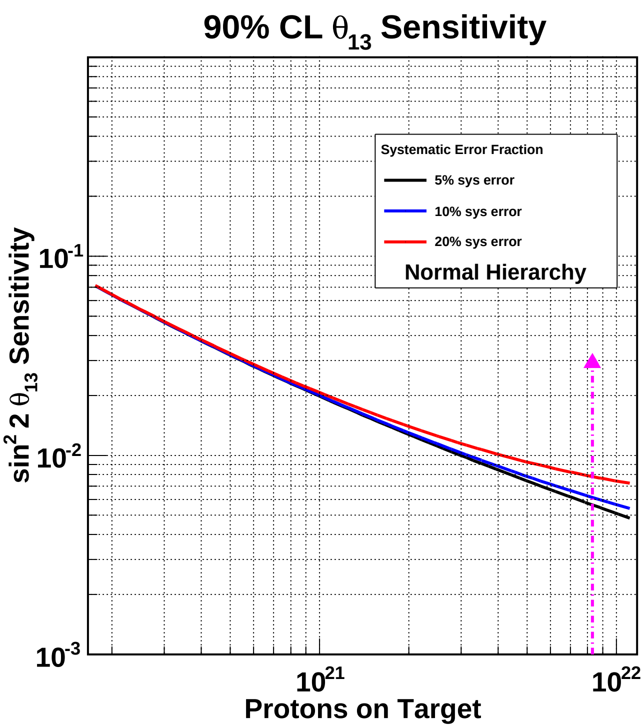

Figure 7: T2K sensitivity to θ_{13} at the 90% confidence level as a function of exposure. 5%, 10% and 20% systematic errors fractions are plotted.

dashed arrow indicates a 5-year run. The following parameters were used: $\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$, $\Delta m^2_{12} \sim 7.6 \times 10^{-5}$, $\sin^2 2\theta_{12} = 0.87$, $\delta = 0$, normal hierarchy. An order of magnitude improvement ($\sin^2 2\theta_{13} = 0.008$ at 90% C.L.) over the CHOOZ limit is expected for aproximately 5-year data taking period. At the same time, the ν_μ disappearance will be measured with the sensitivity $\delta(\Delta m^2_{23}) \sim 1 \times 10^{-4}$ and $\delta(\sin^2 2\theta_{23}) \sim 0.01$.

The T2K neutrino beam line and most elements of ND280 were constructed and successfully comissioned in 2009. T2K started its first physics run in January 2010 and completed in June 2010. It was accumulated about 3.3×10^{19} protons on target for oscillation analysis at a continuous beam power of about 50 kW. The proton beam was precisely tuned to the target with better than 1 mm deviation from the center. Copious neutrino interactions were detected in both central target regions of ND280: POD and FGD. Fig. 8 shows time distribution of neutrino

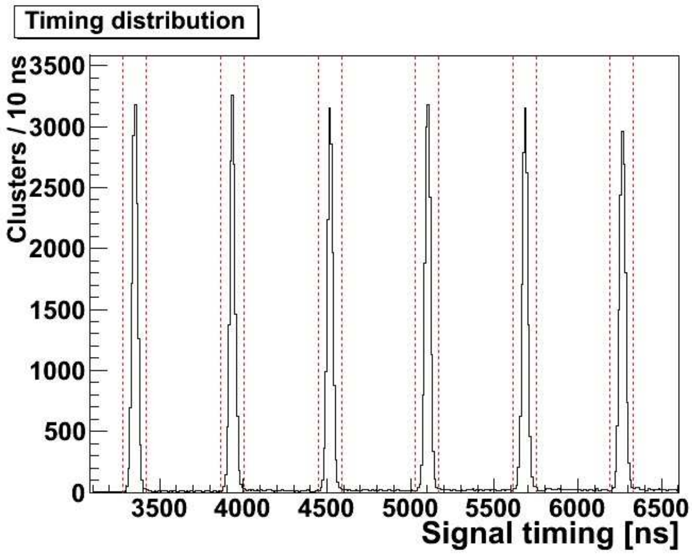

Figure 8: Time distribution of beam neutrino events in FGD corresponds to the proton beam structure: one bunch includes six 56 ns microbunches separated by 580 ns.

events detected by FGD. Very good timing syncronization between the proton beam and SK with resolution of 26 ns was achieved using a GPS system. It was detected 23 events from JPARC muon neutrinos which energy is fully contained in the SK fiducial volume. Detailed information about neutrino events accumulated after the first physics run can be found in Ref. [19, 20]. The oscillation analysis is in progress and the first physics results is expected by 2011. The next physics run is scheduled from November 2010 to July 2011 with the goal to accumulate the integral luminosity of about 150 kW$\times 10^7$ sec that allows to reach the sensitivity of about 0.05 to $\sin^2 2\theta_{13}$.

6.1 Noνa

The primary goal of this experiment [21] is a sensitive search for the $\nu_\mu \to \nu_e$ transition. Noνa can also begin to study the mass hierarchy and a search for CP violation in the lepton sector. Noνa will use the existing NUMI neutrino beam and the optimization of the neutrino spectrum to the oscillation maximum will be realized by optimization of the far detector location from the beam axis. This provides a narrow muon neutrino beam which peaks around 2 GeV at an angle of 14 mrad and has a small ν_e background from kaon decays. Noνa will use two identical detectors: a near detector with a mass of $\sim$ 200 t located at $\sim$ 1 km from NUMI target and a 15 kt far detector at about 810 km from FNAL. The basic unit of the two detectors is a simple rectangular rigid PVC plastic cell containing liquid scintillator (about 80% of the total mass of each detector) and a wavelength-shifting fiber readout.

Taking data with neutrino and antineutrino beams Noνa can distinguish the mass hierarchy using the fact that electron neutrinos and antineutrinos have different interactions with matter. This allows to separate the two hierarchies for large enough value of $\sin^2 2\theta_{13}$. Fig. 9 shows an example of a separation of the mass hierarchies for $P(\nu_\mu \to \nu_e) = 0.2$ and several possible scenarios for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and δ [21]. It should be noted that the value of $\sin^2 2\theta_{13}$ used for this analysis is assumed to be obtained from experiments with reactor neutrinos. The experiment was proposed in 2005 and successfully completed the study and production of prototype detectors. The detector construction started in 2009 and the completion of the far detector is expected in 2013.

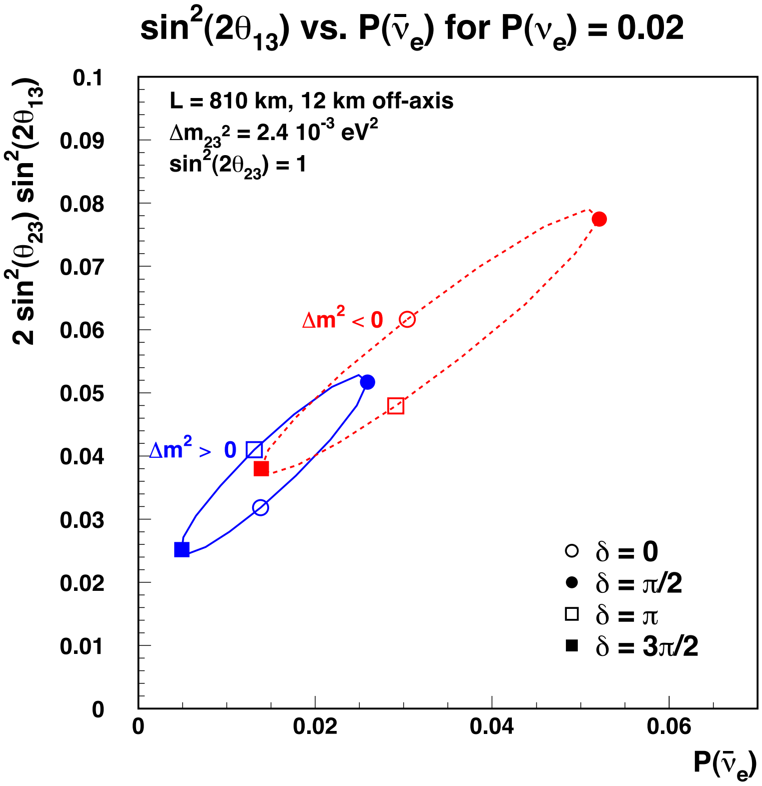

Figure 9: The separation of the mass hierarchies for $P(\nu_\mu \to \nu_e) = 0.2$ and several possible scenarios for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and δ [21]. It is assumed that the value of $\sin^2 2\theta_{13}$ is measured in a reactor experiment.

7 Conclusion

Measurements of neutrino oscillations is the first experimental study of a new physics beyond the Standard Model. Accelerator neutrino experiments (K2K, MINOS) opened the period of precision measurements similar to the CP violation and CKM triangle study in the quark sector. The main goal for upcoming long baseline accelerator neutrino experiments T2K and Noνa is the sensitive search and finally measurement of θ_{13}. It case of a non–zero, and close to the present CHOOZ limit, value of θ_{13}, there is a good chance to resolve the neutrino mass hierarchy and to probe CP violation in the leptonic sector. It should be also mentioned that new sensitive short baseline experiments are required to solve the long standing LSND puzzle.

References

[1] Y. Fukuda et al., Phys. Rev. Lett. **81**, 1562 (1998).

[2] Q.R. Ahmad et al., Phys. Rev. Lett. **87**, 071301 (2001); Phys. Rev. Lett. **89**, 011301 (2002).

[3] K. Eguchi et al., Phys. Rev. Lett. **90**, 021802 (2003).

[4] M.H. Ahh et al., Phys. Rev. D **74**, 072003 (2006); E. Aliu et al., Phys. Rev. Lett. **94** 081802 (2005).

[5] M.H. Ahn et al., Phys. Rev. **D74** 072003 (2006).

[6] D.G. Michael et al., Phys. Rev. Lett. **97** 191801 (2006); hep-ex/0607088.

[7] M. Apollonio et al., Eur. Phys.J. C27 (2003) 331.

[8] P. Vahle, Results from MINOS, talk at NEUTRINO2010, Athens, Greece, 14-19 June 2010.

[9] Y. Takeuchi, Results from SuperKamiokande, talk at NEUTRINO2010, Athens, Greece, 14-19 June 2010.

[10] P. Adamson et al., arXiv:1006.0996 [hep-ex].

[11] M. Guler et al., CERN-SPSC-2000-028; Y. Declais et al., CERN-SPSC-2002-029 SPSC-059.

[12] N. Agafonova et al., arXiv:1006.1623 [hep-ex].

[13] A. Aguilar et al., Phys. Rev. D **64**, 112007 (2001); hep-ex/0104049.

[14] A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. **98** 231801 (2007).

[15] A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. **102** 101802 (2009).

[16] A.A. Aguilar-Arevalo et al., arXiv:1007.1150 [hep-ex].

[17] Y. Itow et al., hep-ex/0106019.

[18] "T2K ND280 Conceptual Design Report", T2K Internal Document. See also D. Karlen, Nucl. Phys. B (Proc. Suppl.) 159 (2006) 91; Yu. Kudenko, Nucl. Instr. Meth. A598 (2009) 289, arXiv:0805.0411 [physics.ins-det].

[19] J. Kameda, Overview of T2K experiment, talk at this conference.

[20] T. Kobayashi, Status of T2K, talk at NEUTRINO2010, Athens, Greece, 14-19 June 2010.

[21] D. Ayres et al., hep-ex/0210005; hep-ex/0503053; http://www-nova.fnal.gov.