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ATMOSPHERIC AND LONG BASELINE NEUTRINO

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ABSTRACT

This paper presents the recent results from Super-Kamiokande atmospheric neutrinos and from K2K accelerator neutrinos. Both results show the signal of neutrino oscillation, and provide new and precise information of oscillation parameters. The oscillation parameters are constraint to be between 1.5×10^{-3} eV^2 and 3.9×10^{-3} eV^2 for Δm^2 and to be greater than 0.92 for $\sin^2 2\theta$.

1 Introduction

After discovery of neutrino oscillation in atmospheric neutrinos by Super-Kamiokande (SK) [1], much attentions are attracted by this new phenomena. In this paper, the new results from SK atmospheric neutrinos and the new result from K2K accelerator long baseline neutrino experiment are presented. The paper only provides the digest of new results, and does not provide the description of the experiments and the analysis. The description of the experiments is found in references [1, 2] and the description of the analysis is found in NEUTRINO 2002 conference [3].

2 Atmospheric Neutrino

The recent results on atmospheric neutrinos from Super-Kamiokande (SK) experiment are presented in this paper. The observation of atmospheric neutrinos by SK is based on 1,489 live-day exposure. The standard selection criteria and analysis techniques are shown in the reference [1], and are not explained in this paper.

At first, the number of contained events with the vertex inside of the fiducial volume of the detector are shown in Table 1. The observed number of muon

Table 1: The number of atmospheric neutrino events and the MC expectation.

Event category	# DATA	# MC (Honda)
Sub-GeV FC 1 ring $e-like$ event	3266	3081.0
Sub-GeV FC 1 ring $\mu-like$ event	3181	4703.9
Sub-GeV FC multi-ring event	2457	2985.6
Sub-GeV FC Total	8904	10770.5
Multi-GeV FC 1 ring $e-like$ event	772	707.8
Multi-GeV FC 1 ring $\mu-like$ event	664	968.2
Multi-GeV FC multi-ring event	1532	1903.5
Multi-GeV FC Total	2968	3579.4
PC event	913	1230.0

Sub-GeV : Deposited Energy in SK is less than 1.33 GeV.
Multi-GeV : Deposited Energy in SK is larger than 1.33 GeV.
FC : Fully Contained events with both the vertex and the stopping point inside of SK.
PC : Partially Contained events with the vertex inside and the stopping point outside of SK.
ring : The number of "ring" corresponds to the number of observed particles.

neutrinos are smaller than the Monte Carlo (MC) prediction. The double ratio of the number of $\mu-like$ events and the number of $e-like$ events between data and

MC are:

$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.638^{+0.016}_{-0.016} \pm 0.050$ (Sub-GeV FC)

$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.658^{+0.030}_{-0.028} \pm 0.078$ (Multi-GeV FC)

The flux of upward through-going muon originated by higher energy neutrinos is $1.7 \pm 0.04 \pm 0.02$ $(\times 10^{-13} cm^{-2} s^{-1} sr^{-1})$ with the expectation of 1.97 ± 0.44 $(\times 10^{-13} cm^{-2} s^{-1} sr^{-1})$. The flux of upward stopping muon is $0.41 \pm 0.02 \pm 0.02$ $(\times 10^{-13} cm^{-2} s^{-1} sr^{-1})$ with the expectation of 0.73 ± 0.16 $(\times 10^{-13} cm^{-2} s^{-1} sr^{-1})$. All measurements show the deficit of muon neutrinos.

The zenith angle distributions are shown in Figure 1 and 2. The distributions are well explained by neutrino oscillation. The best fit point is $\Delta \mathrm{m}^2 = 2.5 \times 10^{-3} eV^2$ and $\sin^2 2\theta = 1.0$ with $\chi^2_{min}. = 163.2/170\ dof$ (dof: degree of freedom). In the case of no oscillation, the χ^2_{min} is $456.5/172\ dof$. Null oscillation scenario is completely ruled out. The contour plot of neutrino oscillation is shown in Figure 3. At 90% C.L., the allowed region of Δm^2 is in the range of $(1.6 - 3.9) \times 10^{-3}$ eV^2, and $\sin^2 2\theta$ is greater than 0.92. The SK oscillation analysis is robust to the uncertainty of the atmospheric neutrino flux calculations and the neutrino interaction cross sections.

Since most favored channel of neutrino oscillation is $\nu_\mu \rightarrow \nu_\tau$, the τ analysis is performed to enhance the fraction of τ events in atmospheric neutrino data. The number of τ neutrino candidates in FC sample is $N_\tau^{FC} = 145 \pm 44(stat.)^{+11}_{-16}(sys.)$ with the MC expectation of 86. The zenith angle distribution of τ candidate is shown in Figure 4. The distribution is consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillation. The three flavor oscillation analysis is performed, and limit on θ_{13} from $\nu_\mu \rightarrow \nu_e$ channel. The result shows no $\nu_\mu \rightarrow \nu_e$ oscillation and it is consistent with CHOOZ and PALOVERDE results. The contour plot is shown in Figure 5.

Finally, the hypothesis of $\nu_\mu \rightarrow \nu_{sterile}$ oscillation channel is tested. The fraction of $\nu_\mu \rightarrow \nu_\tau$ probability is defined as: $\nu_\mu \rightarrow cos\xi \cdot \nu_\tau + sin\xi \cdot \nu_{sterile}$.

The limit on $\nu_\mu \rightarrow \nu_{sterile}$ is $sin^2\xi < 0.19$ at 90% C.L., and the result is shown in Figure 6.

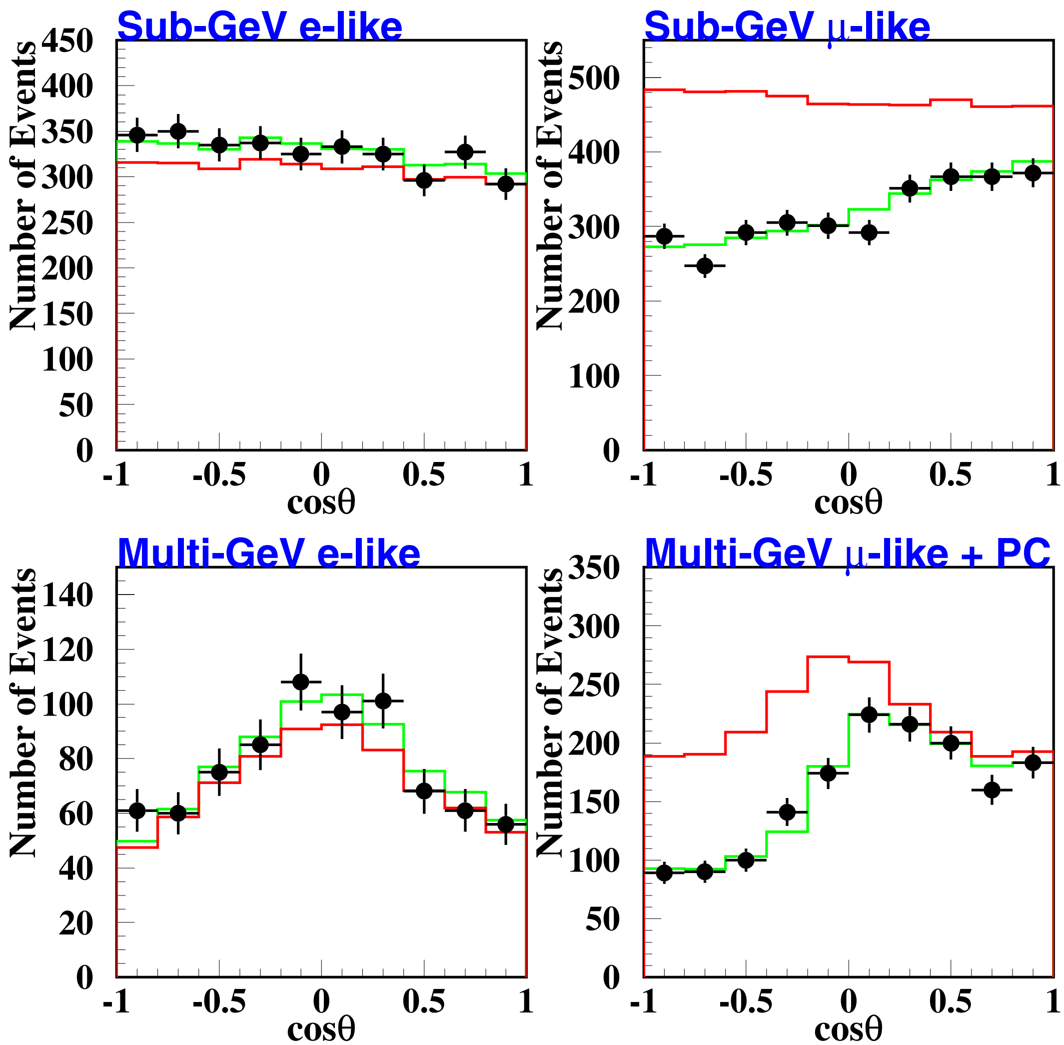

Figure 1: Zenith angle distribution of Sub-GeV single ring e-like events, μ-like events, Multi-GeV single ring e-like events and μ-like events + P.C. events. Closed circle, red histogram and green histogram are data, atmospheric neutrino MC events w/o neutrino oscillation and best fit oscillated expectation with $\Delta m^2 = 2.5 \times 10^{-3} eV^2$ and $\sin^2 2\theta = 1.0$

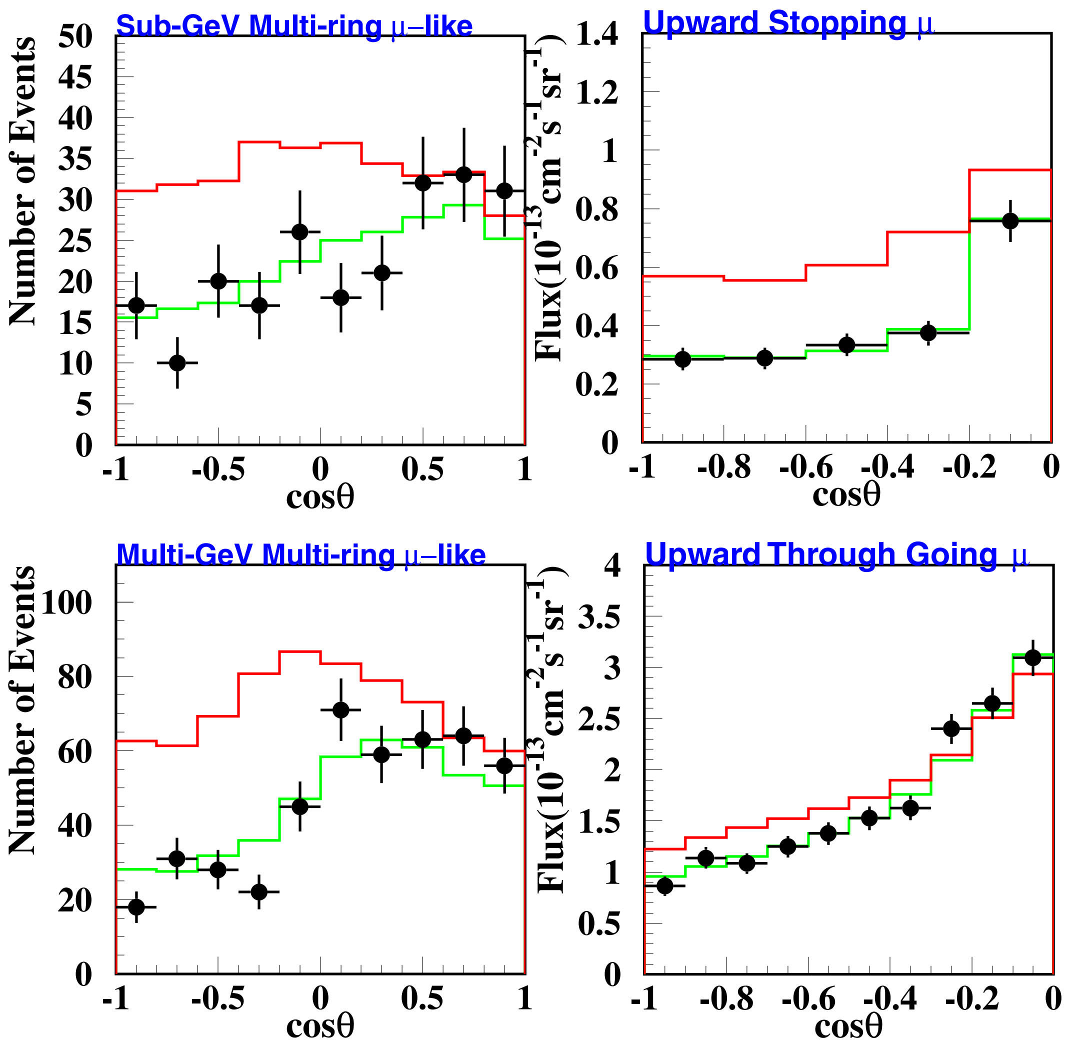

Figure 2: Zenith angle distribution of multi-ring μ-enrich data, upward through going μ and upward stopping μ. Closed circle, red histogram and green histogram are data, atmospheric neutrino MC events w/o neutrino oscillation and best fit oscillated expectation with $\Delta m^2 = 2.5 \times 10^{-3} eV^2$ and $\sin^2 2\theta = 1.0$

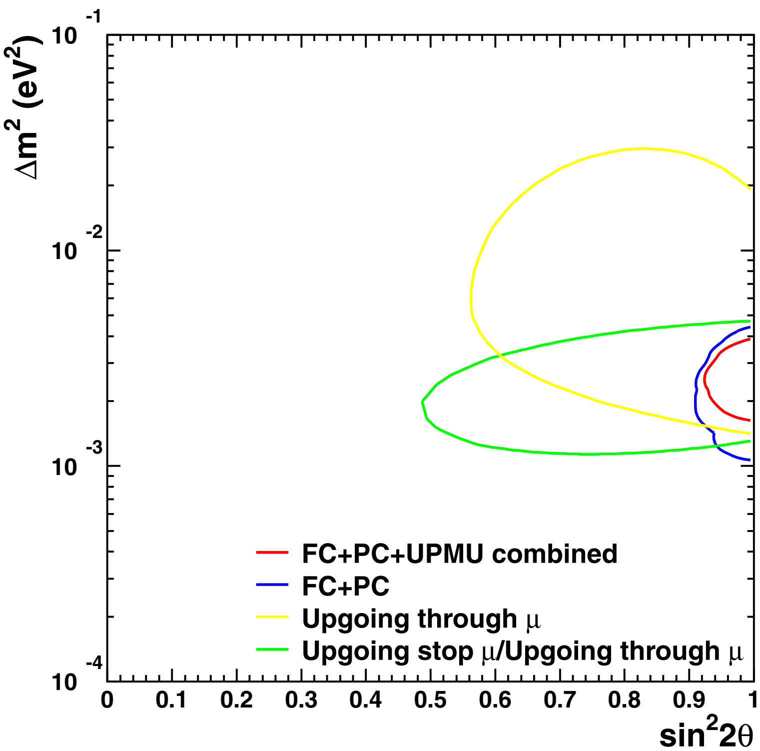

Figure 3: The 68%, 90% and 99% C.L. allowed region using all atmospheric neutrino events (F.C. 1-ring, F.C. multi-ring, P.C., upward through going μ and upward stopping μ) for $\nu_\mu - \nu_\tau$ 2 flavor neutrino oscillation in Super-Kamiokande.

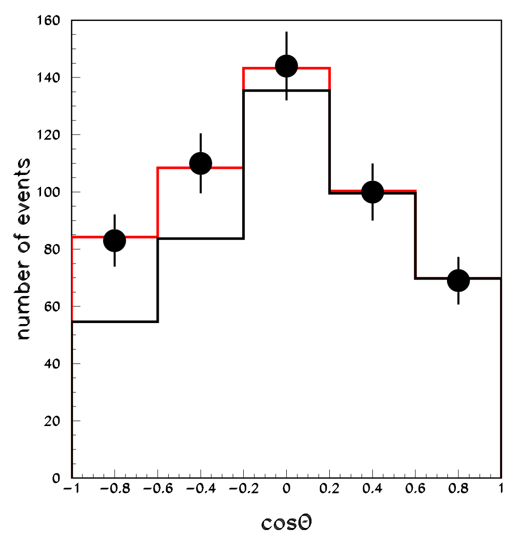

Figure 4: Zenith angle distribution of tau enriched sample. The red histogram is expectation of neutrino oscillation with $\nu_\mu \to \nu_\tau$ channel. The black histogram is without $\nu_\mu \to \nu_\tau$ channel.

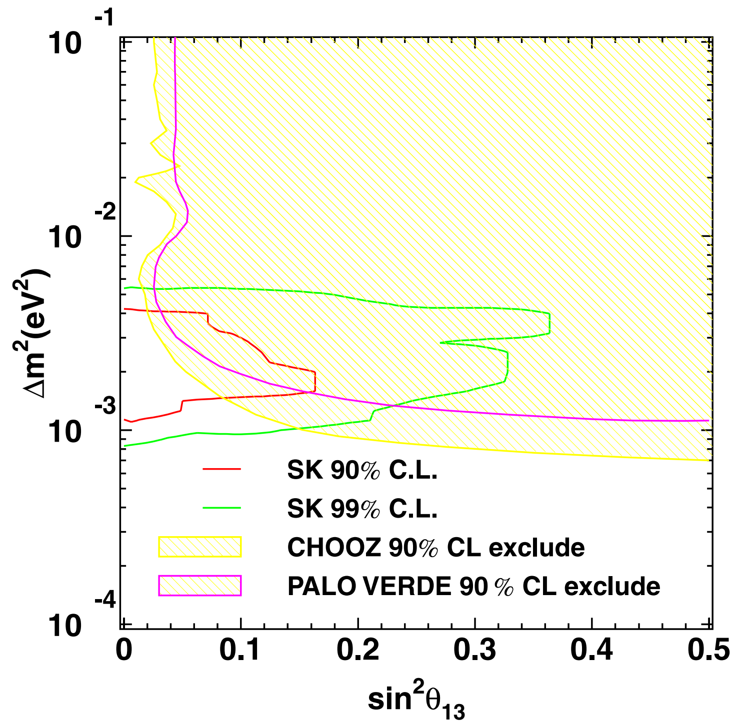

Figure 5: The 90% and 99% C.L. allowed region in three flavor oscillation analysis in Super-Kamiokande. As a reference, the results from CHOOZ and PALOVERDE experiments are overlaid.

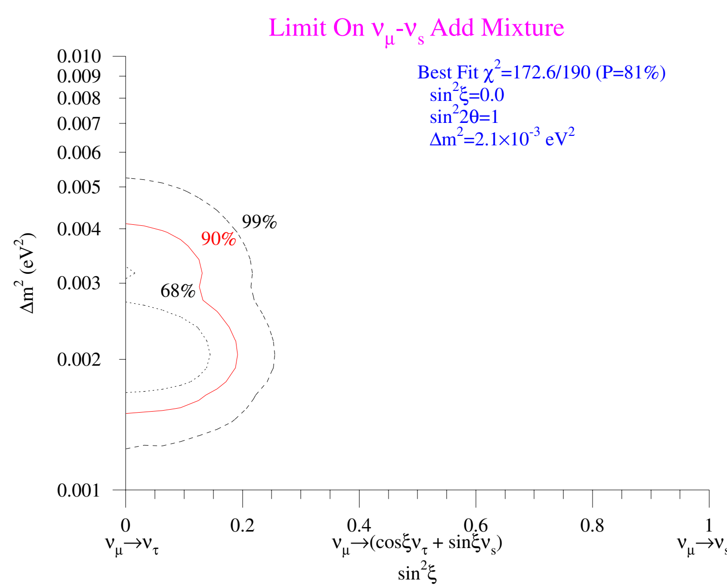

Figure 6: The 68%, 90% and 99% C.L. allowed region of the fraction of the $\nu_\mu \to \nu_\tau$ oscillation channel in $\nu_\mu \to \nu_\tau + \nu_{sterile}$ oscillation.

3 Long Baseline Neutrino

The recent results from K2K, the first accelerator long-baseline neutrino oscillation experiment from KEK to Kamioka, are presented in this paper. The K2K experiment studies neutrino oscillation discovered by atmospheric neutrinos [1]. The details of K2K experiment is described in reference [2]. The neutrino oscillation probability in two flavors is expressed as $P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \cdot \sin^2(\frac{1.27\Delta m^2 L}{E_\nu})$. As a signal of neutrino oscillation in K2K, both the reduction and the energy distortion of muon neutrinos at SK are studied. The data set for this analysis is based on 4.8×10^{19} protons on the target delivered by KEK 12 GeV Proton Synchrotron.

At first, the neutrino flux at KEK is measured by K2K near detectors. The K2K near detectors used for this analysis are 1kt water cherenkov detector (1kt) and the scintillating fiber and water target tracker (SciFi). The muon momentum and the angular distributions measured by 1kt are shown in Figure 7. Single ring $\mu - like$ events are selected by 1kt for this spectrum measurement. In this analysis, the knowledge of neutrino interaction is important since the neutrino energy is reconstructed with an assumption of charged current quasi-elastic (QE) interaction. The reconstructed neutrino energy is defined as:

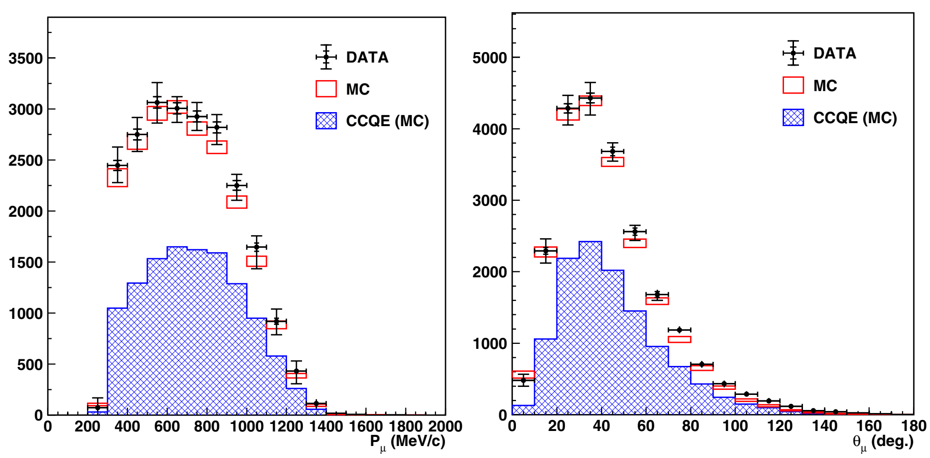

Figure 7: The muon momentum and the angular distributions by K2K 1kt detector. The crosses are data and the boxes are MC simulation with the measured flux. The shaded histogram is the QE contribution in MC events.

$$\mathrm{E}_\nu^{\mathrm{rec}} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + P_\mu cos\theta_\mu}, \tag{1}$$

where $\mathrm{m_N}$, E_μ, m_μ, P_μ and θ_μ are the nucleon mass, muon energy, mass, momentum and scattering angle respectively. We define nonQE interaction as all neutrino interactions excluding the QE interaction. By K2K SciFi detector, the ratio of nonQE interaction to QE interaction is measured as follows. The direction of a proton track is predicted from a muon track with an assumption of QE interaction. We define the angle $\Delta\theta$ as the difference between the prediction and the direction of an observed track. The $\cos(\Delta\theta)$ is shown in Figure 8, in which QE events have a peak at one. By using $\cos(\Delta\theta)$, the SciFi muon events are divided into three categories: one is

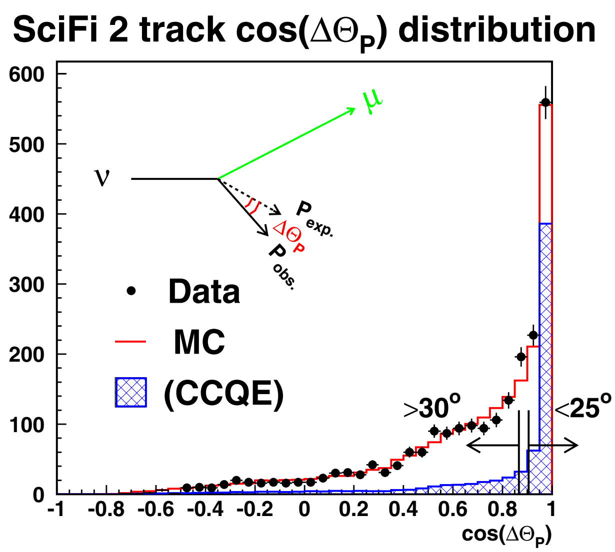

Figure 8: The $\cos(\Delta\theta)$ distribution for two-track events reconstructed in SciFi detector.

one-track sample, the second is two-track QE-enriched sample with $\Delta\theta < 25°$, and the third is two-track nonQE-enriched sample with $\Delta\theta > 30°$. The muon momentum and angular distributions of each sample are shown in Figure 9. The muon momentum and angular distributions of both 1kt and SciFi are used to measure neutrino energy spectrum at KEK. The measured spectrum is shown in Figure 10. The integrated flux for normalization at SK is measured by 1kt.

The neutrino energy spectrum at SK is estimated based on the measured spectrum at KEK multiplying the far/near spectrum ratio estimated by the beam Monte Carlo simulation. The description of the far/near ratio is found in the reference [2]. We observe 56 events at SK in the fiducial volume with an estimate of $80.1^{+5.4}_{-6.2}$ without neutrino oscillation. Twenty-nine single ring muon events in the fiducial volume is used for the spectrum shape analysis. The observed E_ν^{rec} distribution is shown in Figure 11. The MC predictions of both with and without

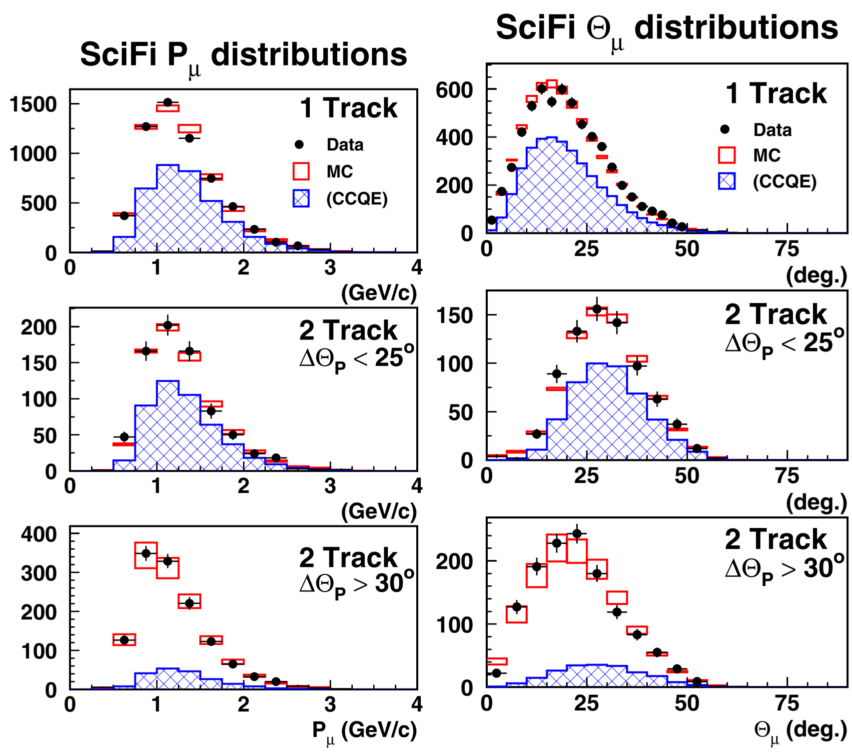

Figure 9: The muon momentum and the angular distributions by K2K SciFi detector. The crosses are data and the boxes are MC simulation with the measured flux. The shaded histogram is the QE contribution in MC events. The SciFi events are divided into three samples: 1-track sample (top), 2-track QE-enriched sample (middle), and 2-track nonQE-enriched sample.

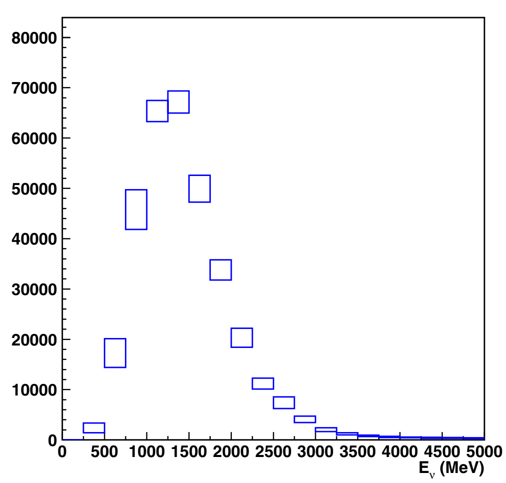

Figure 10: The measured neutrino energy spectrum at KEK by K2K near detectors. The absolute flux (vertical scale) is arbitrary.

neutrino oscillation are overlaid in Figure 11. The observed E_ν^{rec} distribution is better matched to the expected spectrum with neutrino oscillation. The KS rest probability is 79% for spectrum of oscillation.

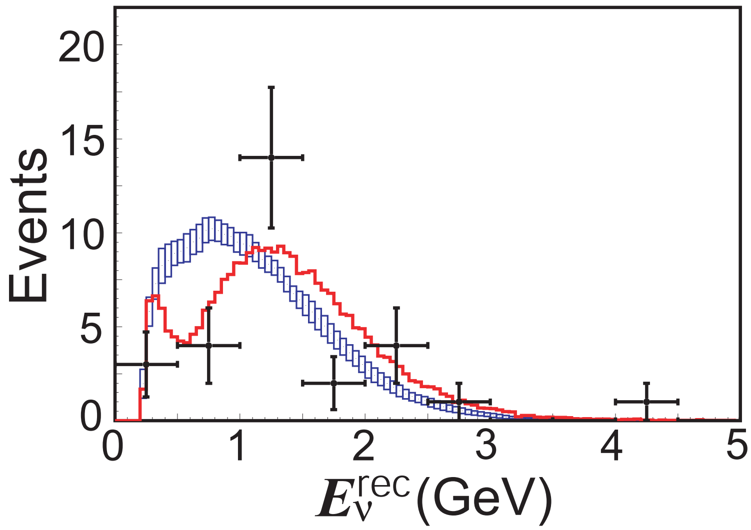

Figure 11: The reconstructed E_ν^{rec} distribution by SK. The dot is data, the box is the MC expectation without neutrino oscillation. The size of the box show the error of the estimation. The red histogram is the expectation of oscillation with the best fit parameters; $\Delta \mathrm{m}^2 = 2.8 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1.0$

The oscillation analysis is performed by the maximum-likelihood method. Both the number of observed events and the E_ν^{rec} distribution is used in this analysis. The likelihood is defined as

$$\mathcal{L} = \mathcal{L}_{norm}(\Delta m^2, \sin^2 2\theta, f) \times \mathcal{L}_{shape}(\Delta m^2, \sin^2 2\theta, f) \times \mathcal{L}_{sys}(f). \tag{2}$$

The normalization term is the Poisson probability to observe $N_{obs}(= 56)$ when expected number of events is $N_{exp}(\Delta m^2, \sin^2 2\theta, f)$. The shape term is the product of the probabilities of each one ring $\mu - like$ (1Rμ) event to be observed at $E_\nu^{rec} = E_i$;

$$\mathcal{L}_{shape} = \prod_{i=1}^{N_{1R\mu}} P(E_i; \Delta m^2, \sin^2 2\theta, f), \tag{3}$$

where P is the normalized E_ν^{rec} distribution estimated by MC simulation and $N_{1R\mu}$ is the number of 1Rμ events. The $\mathcal{L}_{sys}$ is the constraint term by systematic uncertainties. The maximum likelihood fit is used in the analysis of two-flavor oscillation. The allowed region in Δm^2 and $\sin^2 2\theta$ plane is shown in Figure 12 for normalization term and shape term separately. Both the reduction and the energy distortion of muon neutrinos indicate the neutrino oscillation with the same oscillation parameters. The best fit point in combined analysis is $\Delta\mathrm{m}^2 = 2.8 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1.0$. The result is shown in Figure 13. The probability that the measurements at SK were explained by statistical fluctuation without neutrino oscillation is less than 1%. In Figure 13, the allowed region of Δm^2 is between 1.5×10^{-3} and 3.9×10^{-3} eV^2 at 90% C.L. at $\sin^2 2\theta = 1.0$. The delta log likelihood as a function of Δm^2 and $\sin^2 2\theta$ is shown in Figure 14 which indicates the size of errors in this analysis.

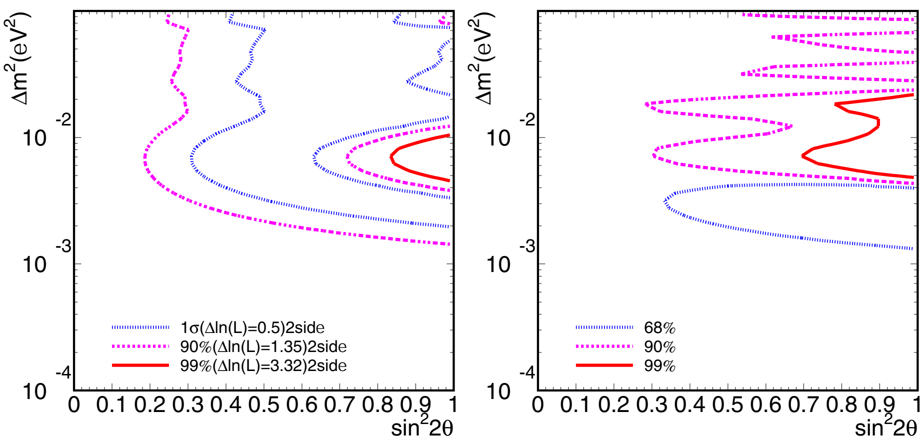

Figure 12: The 68%, 90% and 99% C.L. allowed region from K2K oscillation analysis. The left contour is the result from the normalization analysis,and the right contour is from the shape analysis.

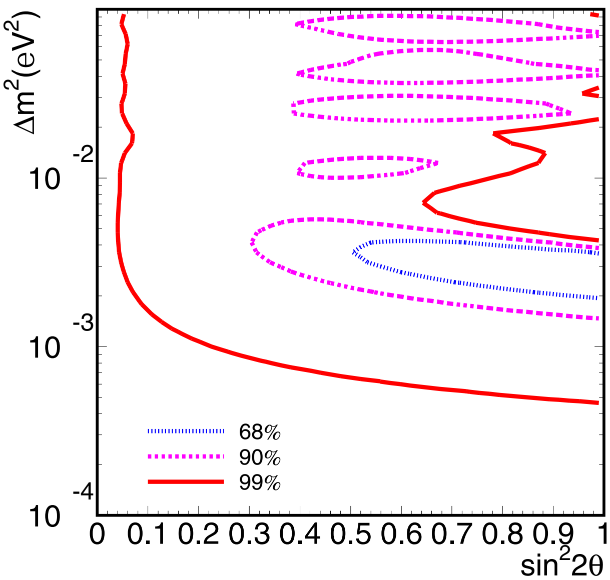

Figure 13: The 68%, 90% and 99% C.L. allowed region from K2K oscillation analysis.

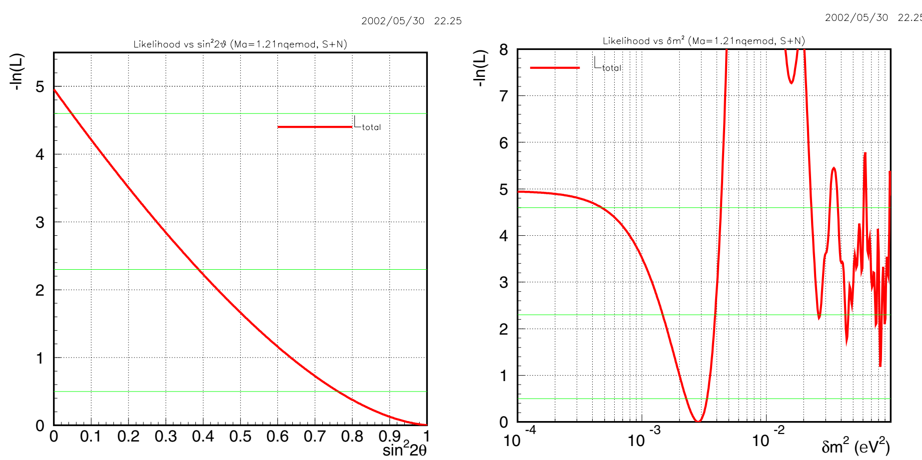

Figure 14: The delta log likelihood as a function of $\sin^2 2\theta$ (left) and Δm^2 (right).

4 Summary

Both SK atmospheric neutrino results and K2K accelerator neutrino results provide new information of neutrino oscillation. The two results are shown in Figure 15, and agree well each other with Δm^2 of $(1.5 - 3.9)\ \times 10^{-3}$ eV^2 at 90% C.L.. The neutrino oscillation is firmly established by SK, and confirmed by K2K at 2.7σ level. The SK plans to resume the observation of atmospheric neutrinos around the end of 2002. The K2K plans to collect twice as many data as this by 2004. Both experiments will provide more precise information of neutrino oscillation.

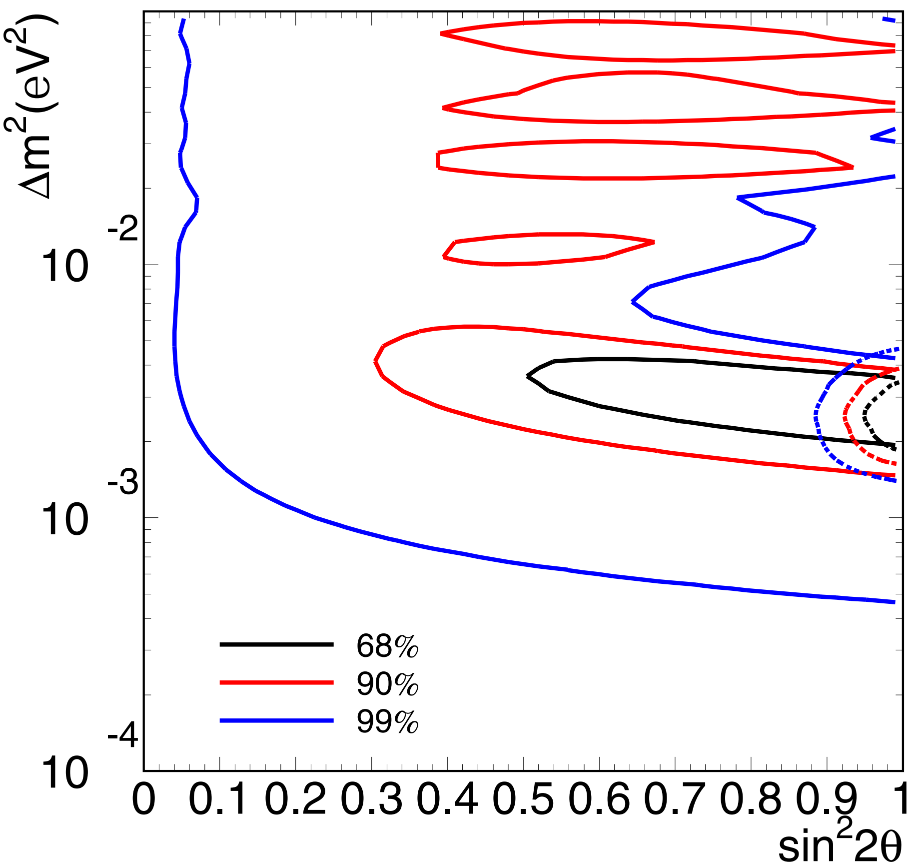

Figure 15: The 68%, 90% and 99% C.L. allowed region. The SK atmospheric neutrino result (dashed line) and K2K accelerator neutrino results (solid line) are overlaid.

References

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2. S.H. Ahn *et al.* (K2K Collaboration), Phys. Lett. **B511**, 178 (2001).

3. NEUTRINO 2002 Conference in Munich, May 2002, http://neutrino2002.ph.tum.de.