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Resent results from Super-Kamiokande on atmospheric neutrinos

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Abstract. Recent Super-Kamiokande results of the study of atmospheric neutrinos and neutrino oscillations are presented. Fully contained events, partially contained events and upward-going muon events are used for neutrino oscillation analyses. The results of a two-flavor and a three flavor oscillation analysis are presented. The data are described well by two flavor $\nu_\mu \to \nu_\tau$ oscillations. The allowed parameter regions are: 1.6×10^{-3} eV$^2 < \Delta m^2 < 3.8 \times 10^{-3}$ eV^2 and $\sin^2 2\theta > 0.90$ at 90% CL. We also present the result of a neutrino decay analysis.

1 Introduction

The Super-Kamiokande detector is a cylindrically-shaped water Cherenkov detector with 50 kiloton of ultra-pure water. It is located about 1000m underground in the Kamioka Observatory in the Kamioka mine in Gifu Prefecture, Japan. The experiment started in April 1996. Super-Kamiokande is a multi purpose experiment, and atmospheric neutrino physics are one of the main topics. Atmospheric neutrinos are produced by the interactions of the primary cosmic rays on nuclei in the atmosphere. The atmospheric neutrinos have remarkable features: (1) the flavor ratio $(\nu_\mu + \overline{\nu_\mu})/(\nu_e + \overline{\nu_e})$ is 2 (greater than 2 above a few GeV) (2) the flux is up/down symmetric in the multi-GeV energy region.

The events which are observed in Super-Kamiokande can be categorized into four types: (1) Fully Contained (FC) events, which have their vertex in the detector and all visible particles are contained in the detector. (2) Partially Contained (PC) events, which have their vertex in the detector and at least one visible particle exits from the detector. (3) Upward through-going muons which are produced by the ν_μ charged current interaction in the rock surrounging the detector and go through the detector. (4) Upward stopping muons which are produced by the ν_μ charged current interaction in the rock surrounging the detector but stop in the detector.

FC events are categorized according to the number of Cherenkov rings, particle ID, and energy. We separate the FC sample into two types: Events with single Cherenkov ring (1-ring events) and Events with more than 1 Cherenkov ring (multi-ring events). Particles are identified as electromagnetic-shower-like (e-like) or non-shower-like (μ-like). Typical neutrino energy is ~1 GeV for 1-ring events, and ~3 GeV for multi-ring events. About 97% of PC events are due to the ν_μ charged current interactions. PC events are more energetic than FC single events, and the energy of a typical PC events is 10 GeV.

The zenith angle of the upward-going muons are limited to $-1 < \cos\Theta < 0$ in order to avoid the huge background from cosmic ray muons. The energy of the parent neutrino is typically 10 GeV for upward stopping and 100 GeV for upward through-going muons, respectively.

2 Data Summary

We have analyzed 1289 days of data for FC and PC events, 1247 days for upward stopping, and 1268 days for upward through-going muons. Table. 1 shows the event summary of FC and PC events. FC sample is separated into two according to the visible energy, E_{vis}. In the 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillation analysis, multi-ring events are used only if the most energetic ring is μ-like. For the sub-GeV 1-ring sample, E_{vis} is less than 1330 MeV and the reconstructed momentum of e-like(μ-like) events is greater than 100 MeV/c(200 MeV/c). For the sub-GeV multi-ring μ-like sample, E_{vis} is within 1330 MeV and 600 MeV, and momentum of the μ-like Cherenkov ring is higher than 600 MeV/c. All multi-GeV samples have $E_{vis} > 1330$ MeV. The direction of multi-ring events is given by the weighted sum of the reconstucted momentum of each Cherenkov ring.

Monte Carlo events are generated based on the calculated flux by M.Honda *et al.* (1995), and normalized by the livetime.

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	Data	Monte Carlo
Sub-GeV		
1-ring		
e-like	2864	2667.6
μ-like	2788	4072.8
Multi-ring		
μ-like	182	289.0
Multi-GeV		
1-ring		
e-like	624	612.8
μ-like	558	838.3
Multi-ring		
μ-like	397	622.7
PC	754	1065.0

Table 1. Summary of FC and PC data. Monte Carlo doesn't include neutrino oscillations and is normalized by the livetime.

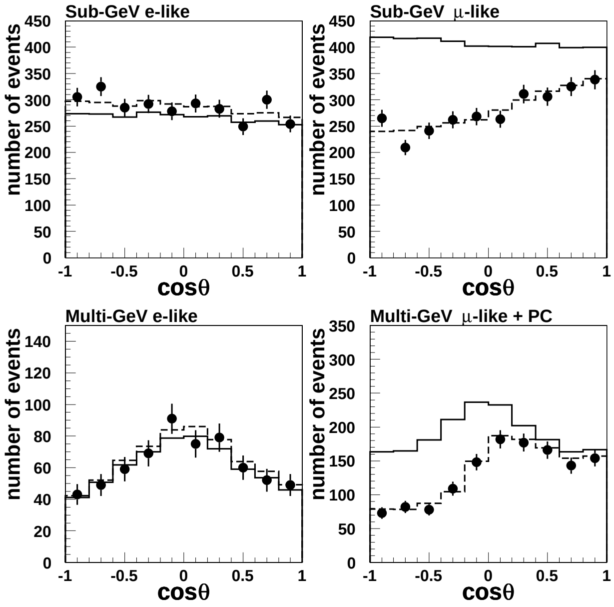

Fig. 1. Zenith angle distribution for FC 1-ring sub-GeV and multi-GeV and PC samples. Points show the data, solid histograms show the expected values from null oscillation Monte Carlo, and dashed lines show the best fit ($\sin^2 2\theta$=1.0, $\Delta m^2 = 2.5 \times 10^{-3}$eV^2) from the $\nu_\mu \to \nu_\tau$ oscillation analysis.

Table. **??** shows the summary of the observed flux of upward through-going and stopping muons. The track length of muons in the inner detector is required to be greater than 7m which corresponds to 1.6 GeV muon energy. The flux is the averaged over $-1 < \cos\Theta < 0$. The expected flux is based on the Honda flux.

Fig. 1, Fig. **??**, and Fig. 3 show the zenith angle distributions for each sample. Points show the data, solid histograms show the expected values from null oscillation Monte Carlo, and dashed lines show the best fit from the $\nu_\mu \to \nu_\tau$ oscillation analysis.

3 $\nu_\mu \leftrightarrow \nu_\tau$ 2-flavor oscillation analysis

We carried out a χ^2 test for $\nu_\mu \leftrightarrow \nu_\tau$ 2-flavor oscillation using FC, PC, and upward-muons Y.Fukuda *et al.* (1998).

The FC 1-ring sample is divided into 135 zenith angle and momentum bins. The PC sample is divided into 10 zenith angle bins. The upward through-going(stopping) muon sample is divided into 10(5) zenith angle bins. The FC multi-ring μ-like sample is divided into 10 zenith angle bins (for both sub-GeV and multi-GeV). We searched for the minimum χ^2 in the $(\sin^2 2\theta, \Delta m^2)$ space. In the calculation of χ^2, a common absolute normalization factor was used as a free parameter. The minimum χ^2 is 159.2/175 d.o.f. at $(\sin^2 2\theta, \Delta m^2)$ = (1.0,2.5×10^{-3}eV^2). The best fit zenith angle distributions are shown in Fig. 1, Fig. **??**, and Fig. 3. Data and the expectation from $\nu_\mu \to \nu_\tau$ oscillation agree well, and all samples are consitently described by $\nu_\mu \to \nu_\tau$ oscillation.

Upward thr.going muons flux (10^{-13}cm^{-2}sec^{-1}sr^{-1})	
Observed	1.70 $\pm$0.05$_{\text{(stat.)}}$ $\pm$0.02$_{\text{(sys.)}}$
Expected	1.84 $\pm$0.41$_{\text{(sys.)}}$

Upward stopping muons flux (10^{-13}cm^{-2}sec^{-1}sr^{-1})	
Observed	0.41 $\pm$0.02$_{\text{(stat.)}}$ $\pm$0.02$_{\text{(sys.)}}$
Expected	0.68 $\pm$0.15$_{\text{(sys.)}}$

Table 2. Summary of the averaged flux of upward-going muons. Flux is averaged over $-1.0 < \cos\Theta < 0.0$.

Fig. 4 shows the contour plots of the allowed region of the oscillation parameters, $(\sin^2 2\theta, \Delta m^2)$. The allowed parameter region is 1.6×10^{-3}eV^2 $< \Delta m^2 <$ 3.8×10^{-3}eV^2 and $\sin^2 2\theta > 0.90$ at 90% C.L..

4 3-flavor oscillation analysis

We also carried out a 3-flavor oscillation analysis using the FC 1-ring, multi-ring e-like, and PC events. In this analysis, we assumed that the mass difference between the lightest and the second lightest neutrino is very small and the effect of the oscillation between these two mass eigenstates is invisible in atmospheric neutrinos. In this approximation, the oscillation probability is parameterized by 3 parameters, $\sin^2\theta_{13}, \sin^2\theta_{23}$, and $\Delta m^2 \equiv \Delta m^2_{13} = \Delta m^2_{23}$. We scanned this three-dimensional parameter space, and Fig. 4 shows the allowed region projected on the $(\sin^2\theta_{13}, \Delta m^2)$ plane. The observed zenith angle distributions of e-like events are consistent with the expectation from null oscillation Monte Carlo, and there is no evidence for non-zero $\sin^2\theta_{13}$. The allowed region for $\sin^2\theta_{13}$ obtained in the analysis is consistent with the CHOOZ(M.Appolonio *et al.* (1999)) and Palo-Verde(F.Boehm *et al.* (2000)) results.

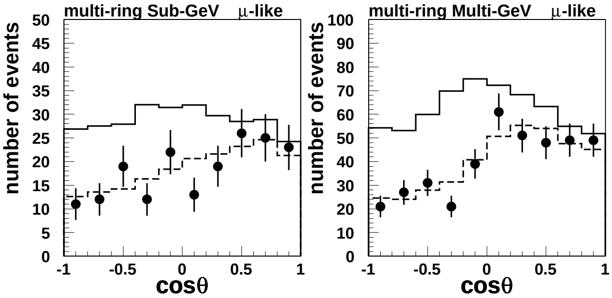

Fig. 2. Zenith angle distribution for FC multi-ring μ-like sub-GeV and multi-GeV samples. Points show the data, solid histograms show the expected values from null oscillation Monte Carlo, and dashied lines show the best fit ($\sin^2 2\theta$=1.0, $\Delta m^2 = 2.5 \times 10^{-3}$eV^2) from the $\nu_\mu \rightarrow \nu_\tau$ oscillation analysis.

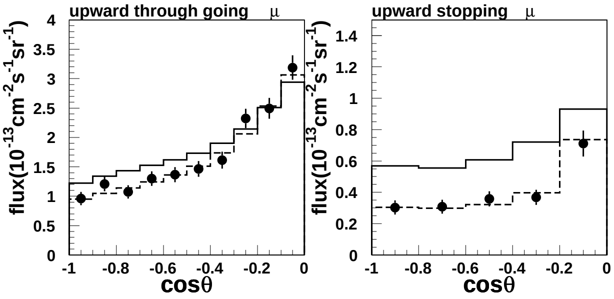

Fig. 3. Zenith angle distribution for Upward-going muons. Points show the data, solid histograms show the expected values from null oscillation Monte Carlo, and dashied lines show the best fit ($\sin^2 2\theta$=1.0, $\Delta m^2 = 2.5 \times 10^{-3}$eV^2) from the $\nu_\mu \rightarrow \nu_\tau$ oscillation analysis.

5 Neutrino Decay

It was pointed out that neutrino decay to a sterile state with $\Delta m^2 \rightarrow 0$ gives one possible solution of the observed anormaly of the atmospheric muon neutrinos(V.Barger *et al.* (1999)). Assuming that ν_2 has some decay channels, the survival probability for $\Delta m^2 \rightarrow 0$ case is written as:

$$P(\nu_\mu \rightarrow \nu_\mu) = \left(\sin^2\theta + \cos^2\theta \exp\left(-\frac{m_2}{2\tau_2}\frac{L_\nu}{E_\nu}\right)\right)^2 \qquad (1)$$

where θ is the mixing angle, τ_2 and m_2 are the lifetime and the mass of ν_2, L_ν and E_ν are the flight length and energy of the neutrino, respectively. The result from FC 1-ring+PC+upward-muons analysis gives minimum χ^2 = 147.1/153 d.o.f. at ($\sin^2\theta, m/\tau$) = (0.68, 0.01(GeV/km)), suggesting that neutrino decay could explain the observed events of FC 1-ring, PC, and upward-muons.

To further test for neutrino decay, we carried out another analysis using the multi-ring Neutral Current(NC) enriched sample. The selection criteria for the multi-ring NC sample are (1) FC multi-ring, (2) $E_{\rm vis} > 400$MeV, and (3) the most energetic ring is e-like. The fraction of NC is estimated to be 29%(Y.Fukuda *et al.* (2000)).

Neutrino decay to a sterile state decreases the number of upward going NC interactions, while the $\nu_\mu \rightarrow \nu_\tau$ oscillations don't. Fig. 6 shows the upward/downward ratio as a function of m/τ. Upward(downward) is defined as the region where the cosine of the zenith angle < -0.4(> +0.4).

Fig. 7 shows the excluded region of the parameter plane by the analysis of the multi-ring NC enriched sample One sees that the parameters allowed by the FC+PC+upward-muon analysis is excluded at 99% C.L. by the multi-ring NC enriched sample.

6 Summary

We presented our resent atmospheric neutrino results. The results clearly demonstrate the validity of the $\nu_\mu \rightarrow \nu_\tau$ oscillation, and the neutrino decay hypothesis is excluded at 99% C.L.. No evidence for non-zero $\sin^2\theta_{13}$ is found from the 3-flavor oscillation analysis.

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References

M.Appolonio *et al.*, Phys. Lett. B 466, 137.
V.Barger *et al.*, Phys. Lett. B462(1999), 109.
F.Boehm *et al.*, Phys. Rev. Lett. 84(2000),3764
Y.Fukuda *et al.*, Phys. Rev. Lett. 81(1998),1562
Y.Fukuda *et al.*, Phys. Rev. Lett. 85(2000),3999
M.Honda *et al.*, Phys. Rev. D52(1995),4985.

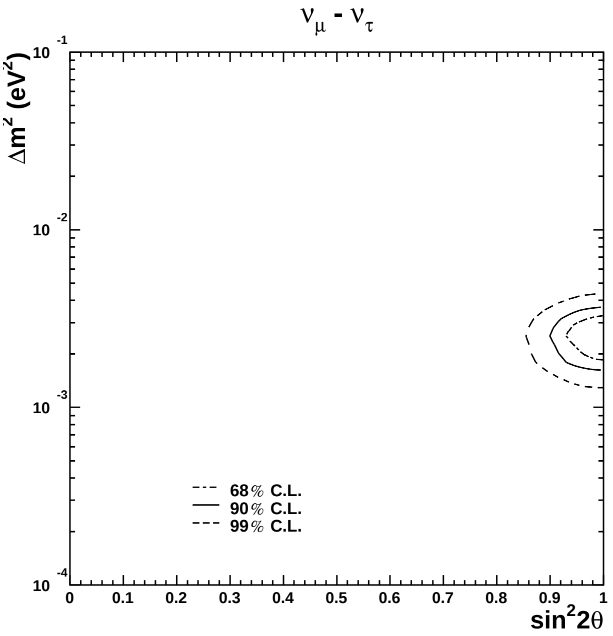

Fig. 4. Contour plots of the allowed region of ($\sin^2 2\theta, \Delta m^2$) plane. The dotted line shows the 68% C.L., the solid line shows the 90% C.L., and the dashed line shows the 99% C.L. respectively. The best fit point is at ($\sin^2 2\theta, \Delta m^2$) = (1.0,2.5$\times 10^{-3}$eV^2).

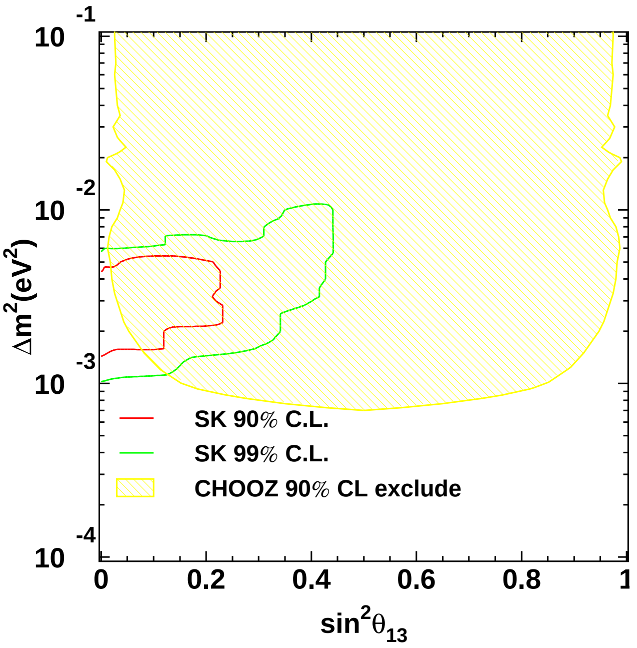

Fig. 5. Contour plots of allowed region projected on ($\sin^2 \theta_{13}, \Delta m^2$) plane. The solid and dashed lines show 90% and 99% C.L. allowed region from Super-Kamiokande, respectively. The hatched region shows the excluded region by the CHOOZ experiment(M.Appolonio *et al.* (1999)).

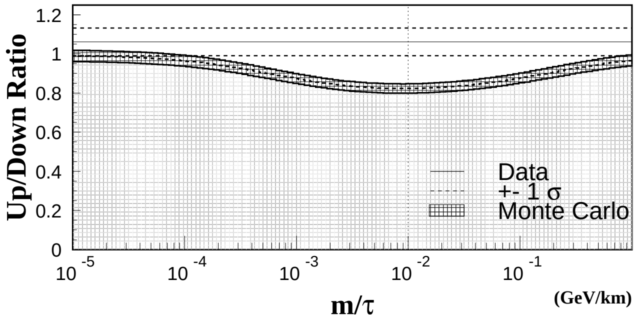

Fig. 6. Predicted $Up/Down$ ratio from neutrino decay as a function of m/τ with $\sin^2\theta$=0.68. The horizontal solid line shows the observed ratio(=1.06) and the dotted lines show the $\pm 1\sigma$ error including both statistical and experimental systematic errors. The hatched curve shows the prediction from the neutrino decay Monte Carlo with systematic uncertainty(2.9%). The vertical dotted line shows the best fit m/τ from the FC 1-ring+PC+upward-muon analysis.

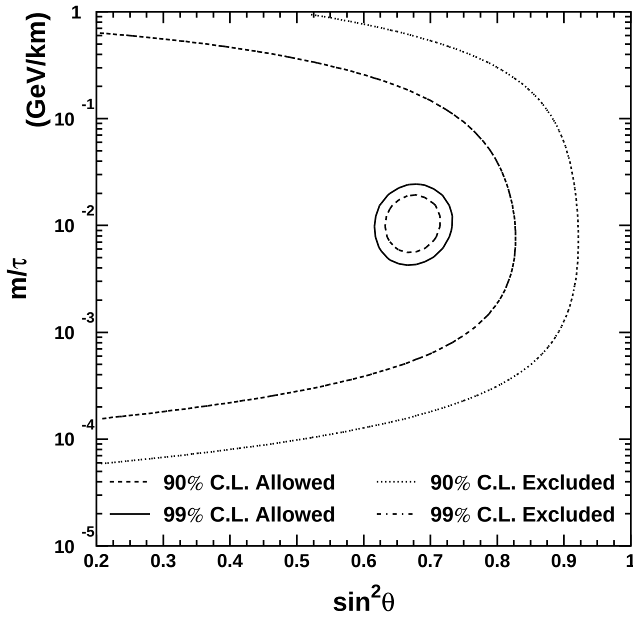

Fig. 7. Contour plots of the excluded region from the multi-ring NC events analysis. The outer(inner) curve shows the 90%(99%) C.L. excluded region from the multi-ring NC analysis. The inner(outer) circle shows the 90%(99%) C.L. allowed region from the FC 1-ring+PC+upward-muons analysis.