Evidence for an oscillatory signature in atmospheric neutrino oscillation

Y. Ashie,1 J. Hosaka,1 K. Ishihara,1 Y. Itow,1 J. Kameda,1 Y. Koshio,1 A. Minamino,1 C. Mitsuda,1 M. Miura,1 S. Moriyama,1 M. Nakahata,1 T. Namba,1 R. Nambu,1 Y. Obayashi,1 M. Shiozawa,1 Y. Suzuki,1 Y. Takeuchi,1 K. Takii,1 S. Yamada,1 M. Ishitsuka,2 T. Kajita,2 K. Kaneyuki,2 S. Nakayama,2 A. Okada,2 K. Okumura,2 T. Ooyabu,2 C. Saji,2 Y. Takenaga,2 S. Desai,3 E. Kearns,3 S. Likhoded,3 J. L. Stone,3 L. R. Sulak,3 C. W. Walter,3 W. Wang,3 M. Goldhaber,4 D. Casper,5 J. P. Cravens,5 W. Gajewski,5 W. R. Kropp,5 D. W. Liu,5 S. Mine,5 M. B. Smy,5 H. W. Sobel,5 C. W. Sterner,5 M. R. Vagins,5 K. S. Ganeza,6 J. Hill,6 W. E. Keig,6 J. S. Jang,7 J. Y. Kim,7 J. T. Lim,7 R. W. Ellsworth,8 S. Tasaka,9 G. Guillian,10 A. Kibayashi,10 J. G. Learned,10 S. Matsuno,10 D. Takemori,10 M. D. Messier,11 Y. Hayato,10 A. K. Ichikawa,12 T. Ishida,12 T. Ishii,12 I. Kato,12 A. K. Ichikawa,12 T. Kobayashi,12 T. Maruyama,12 Y. Nakamura,12 K. Nitta,12 Y. Oyama,12 M. Sakuda,12 Y. Totsuka,12 A. T. Suzuki,13 M. Hasegawa,14 K. Hayashi,14 T. Inagaki,14 I. Kato,14 H. Maesaka,14 T. Morita,14 T. Nakaya,14 K. Nishikawa,14 T. Sasaki,14 S. Ueda,14 S. Yamamoto,14 T. J. Haines,15, S. Dazeley,16 S. Hatakeyama,16 R. Svoboda,16 E. Blaufuss,17 J. A. Goodman,17 G. W. Sullivan,17 D. Turcan,17 K. Scholberg,18 A. Habig,19 Y. Fukuda,20 C. K. Jung,21 T. Kato,21 K. Kobayashi,21 M. Malek,21 C. McGuire,21 A. Sarrat,21 E. Sharkey,21 C. Yanagisawa,21 T. Toshito,22 K. Miyano,23 N. Tanaka,23 J. Ishii,24 Y. Kuno,24 Y. Nagashima,24 M. Takita,24 M. Yoshida,24 S. B. Kim,25 J. Yoo,25 H. Okazawa,26 T. Ishizuka,27 Y. Choi,28 H. K. Seo,28 Y. Gando,29 T. Hasegawa,29 K. Inoue,29 J. Shirai,29 A. Suzuki,29 M. Koshiba,30 Y. Nakajima,31 K. Nishijima,31 T. Harada,32 H. Ishino,32 R. Nishimura,32 Y. Watanabe,32 D. Kieleczewska,33,35 J. Zalipska,33 H. G. Berns,34 R. Gran,34 K. K. Shiraishi,34 A. Stachyra,34 K. Washburn,34 and R. J. Wilkes34
(The Super-Kamiokande Collaboration)

1 Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Kamioka, Gifu, 506-1205, Japan
2 Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan
3 Department of Physics, Boston University, Boston, MA 02215, USA
4 Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
5 Department of Physics and Astronomy, University of California, Irvine, Irvine, CA 92697-4575, USA
6 Department of Physics, California State University, Dominguez Hills, Carson, CA 90747, USA
7 Department of Physics, Chonnam National University, Kwangju 500-757, Korea
8 Department of Physics, George Mason University, Fairfax, VA 22030, USA
9 Department of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
10 Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA
11 Department of Physics, Indiana University, Bloomington, IN 47405-7105, USA
12 High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
13 Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan
14 Department of Physics, Kyoto University, Kyoto 606-8502, Japan
15 Physics Division, P-23, Los Alamos National Laboratory, Los Alamos, NM 87544, USA
16 Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA
17 Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
18 Department of Physics, University of Minnesota, Duluth, MN 55812-2496, USA
19 Department of Physics, Miyagi University of Education, Sendai, Miyagi 980-8565, Japan
20 Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794-3800, USA
21 Department of Physics, Nagoya University, Nagoya, Aichi 464-8602, Japan
22 Department of Physics, Niigata University, Niigata, Niigata 950-2181, Japan
23 Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
24 Department of Physics, Seoul National University, Seoul 151-742, Korea
25 Department of Physics, Seoul National University, Seoul 151-742, Korea
26 International and Cultural Studies, Shizuoka Seika College, Yaizu, Shizuoka 425-8611, Japan
27 Department of Physics, Shizuoka University, Hamamatsu, Shizuoka 432-8561, Japan
28 Department of Physics, Sunykyunkwan University, Suwon 440-746, Korea
29 Research Center for Neutrino Science, Tohoku University, Sendai, Miyagi 980-8578, Japan
30 University of Tokyo, Tokyo 113-0033, Japan
31 Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan
32 Department of Physics, Tokio Institute for Technology, Meguro, Tokyo 152-8551, Japan
33 Institute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland
34 Department of Physics, University of Washington, Seattle, WA 98195-1560, USA

(Dated: March 25, 2022)

Muon neutrino disappearance probability as a function of neutrino flight length $L$ over neutrino energy $E$ was studied. A dip in the $L/E$ distribution was observed in the data, as predicted from
Recent neutrino experiments using atmospheric [1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12], solar [1, 2, 5, 6, 7, 8, 9, 10], reactor [13], and accelerator neutrinos [14], have demonstrated that neutrinos change flavor as they travel from the source to the detector, a phenomenon consistent with the hypothesis of neutrino oscillation. Neutrino oscillation is a natural consequence of neutrinos that have finite mass and flavor eigenstates that are superpositions of the mass eigenstates. The phenomenon is referred to as oscillation because the survival probability of a given flavor, such as $\nu_{\mu}$, is given by:

$$P(\nu_{\mu} \rightarrow \nu_{\mu}) = 1 - \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 (eV^2) L (km)}{E (GeV)} \right),$$

where $E$ is the neutrino energy, $L$ is the travel distance, $\Delta m^2$ is the difference of the squared mass eigenvalues, and $\theta$ is the mixing angle between flavor and mass states. This equation is true in vacuum for all cases, is true in matter for $\nu_{\mu} \leftrightarrow \nu_\tau$, but may be modified for oscillation involving $\nu_e$ which travel through matter.

However, the sinusoidal $L/E$ dependence of the survival probability has not yet been observed. For solar neutrinos, the survival probability is non-sinusoidal as the two eigenstates in matter are no longer coherent after many oscillation cycles [15]. Reactor and accelerator neutrino experiments have insufficient statistics at this time. The standard analysis of the large sample of atmospheric neutrinos recorded by the Super-Kamiokande experiment has not been optimized to resolve the effect, although the zenith angle dependence strongly indicates maximal $\nu_{\mu} \leftrightarrow \nu_\tau$ mixing with $\Delta m^2$ in the vicinity of 2 to $2.5 \times 10^{-3}$ eV$^2$. The analysis described herein used a selected sample of these atmospheric neutrino events, those with good resolution in $L/E$, to search for the dip in oscillation probability expected when the argument of the second sine-squared term in Eq. (1) is $\pi/2$.

Super-Kamiokande (Super-K) is a cylindrical 50 kton water Cherenkov detector located at a depth of 2700m water equivalent. The water tank is optically separated into two concentric cylindrical detector regions. The inner detector (ID) is instrumented with 11,146 inward facing 20 inch diameter photomultiplier tubes (PMT). The outer detector (OD) is instrumented with 1,885 outward facing 8 inch PMTs.

In the present analysis, 1489 live-day exposure of fully contained (FC) $\mu$-like and partially contained (PC) atmospheric neutrino data were used. FC events deposit all of their Cherenkov light inside the ID, while PC events have an exiting particle that deposits visible energy in the OD. The direction and the momentum of charged particles were reconstructed from the Cherenkov ring image. Each observed ring was identified as either $e$-like or $\mu$-like based on the shape of the ring pattern. For FC multi-ring events, the particle type of the most energetic ring was used to identify $\mu$-like events. Since more than 97% of PC events were estimated to be $\nu_\mu$ charged current (CC) interactions, all PC events were classified as $\mu$-like. The atmospheric neutrino prediction in Super-K is modeled using a Monte Carlo (MC) simulation [16].

Event selection and classification in the present analysis are slightly different from those in the Super-K standard oscillation analysis using zenith angle distributions. The fiducial volume for the FC events was expanded from 22.5 kton to 26.4 kton (event vertex should be more than 1.5 m from the top and bottom walls of the ID and 1 m from the side wall) in order to increase the statistics of the data, especially of high energy muons. Estimated non-neutrino background in the expanded fiducial volume was negligibly small, less than 0.1%. PC events were classified into two categories using the OD charge (photoelectron) information: “OD stopping events” and “OD through-going events”. Muons in the “OD stopping events” have stopped in the OD, while muons in the “OD through-going events” have passed through the OD. Figure 1 shows the ratio of the observed charge in the OD to the expectation from the projected track length in the OD. Events with lower charge than the criterion were classified as “OD stopping events”. Since these two samples have different resolution in $L/E$, different cuts were applied for each sample, improving the overall efficiency.

The neutrino energy was estimated from the total energy of charged particles observed in the ID. The energy deposited in the OD was taken into account for PC events. The projected track length in the OD was used to estimate the energy deposited in the OD. The relationship between the neutrino energy and the observed energy was determined based on the MC simulation. The flight length of neutrinos, which ranges from approximately 15 km to 13,000 km depending on the zenith angle, was estimated from the reconstructed neutrino direction. The neutrino direction was taken to be along the total momentum vector from all observed particles. The resolution of the reconstructed $L/E$ was calculated at each point in the $(\cos \Theta, E)$ plane, where $\Theta$ is the zenith angle. The energy resolution becomes poorer for higher energy PC events, due mainly to the saturation in the electronics that records the PMT charge. Therefore, extremely high energy events (observed energy > 50 GeV)
osci. oscillation is not included in the MC. Numbers in the parenthesis. The MC does not include oscillations and is normalized by the live-time. Neutrino is normalized by the live-time.

FIG. 1: Observed charge (photoelectrons) in the OD divided by the expectation from the projected track length in the OD for the data (points), the OD through-going MC events (white region in histogram) and the OD stopping MC events (hatched region). The MC does not include oscillations and is normalized by the live-time.

FIG. 2: Contour plots of 70 % L/E resolution in the (cos Θ, Eν) plane for (a) FC single-ring, (b) FC multi-ring, (c) PC OD stopping and (d) PC OD through-going samples. Three additional lines in (a) show the survival probabilities of muon neutrinos predicted from neutrino oscillation with (sin^2 2θ, Δm^2) = (1.00, 2.4 × 10^{-3} eV^2). Full and half oscillation occur on the solid and dashed lines, respectively.

dL/dΘ for horizontal-going events or large scattering angles for low energy events. The bold solid central line indicates the minimum survival probability of muon neutrinos predicted from neutrino oscillations with Δm^2 = 2.4 × 10^{-3} eV^2. It is clear that detecting high energy muon events is crucial to observe the first maximum oscillation in L/E. The resolution cut of Δ(L/E) < 70% was determined from the MC simulation to maximize the sensitivity to distinguish neutrino oscillation from other hypotheses.

Table I summarizes the number of events used in this analysis after the L/E resolution cut. Figure 4 shows 70 % was determined from the MC simulation to maximize the sensitivity to distinguish neutrino oscillation from other hypotheses. Three additional lines in (a) show the survival probabilities of muon neutrinos predicted from neutrino oscillation with (sin^2 2θ, Δm^2) = (1.00, 2.4 × 10^{-3} eV^2). Full and half oscillation occur on the solid and dashed lines, respectively.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

Below 150 km/GeV, the data and MC agree well. In Fig. 4 the data over non-oscillated MC ratio as a function of L/E is plotted together with the best-fit expectation for 2-flavor νμ ↔ ντ oscillations with systematic errors. A dip, which should correspond to the first maximum oscillation, is observed around L/E = 500 km/GeV. We note that the position of the dip is about a factor of 3 to 4 away from that of the predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

Table I summarizes the number of events used in this analysis after the L/E resolution cut. Figure 4 shows 70 % was determined from the MC simulation to maximize the sensitivity to distinguish neutrino oscillation from other hypotheses. Three additional lines in (a) show the survival probabilities of muon neutrinos predicted from neutrino oscillation with (sin^2 2θ, Δm^2) = (1.00, 2.4 × 10^{-3} eV^2). Full and half oscillation occur on the solid and dashed lines, respectively.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.

In order to confirm that the observed dip was not due to systematic effects, several tests were carried out. Several L/E distributions were made by changing the L/E resolution cut value. Plots based on the resolution cuts at 60, 80 and 90% showed consistent dip structures as that predicted event number minimum as seen in Fig. 3. Due to the L/E resolution of the detector, the second and higher maximum oscillation points should not be observable in this experiment.
Finally, the $L/E$ plot was made using FC single-ring $e$-like events. The $e$-like distribution was consistent with flat over the whole $L/E$ range. Thus we are confident that the observed dip is not due to systematic effects in the event selection.

The data/prediction at large $L/E$ in Fig. 4 shows a slight rise from the expected flat distribution. We have studied possible causes of this deviation, and concluded that an energy-dependent systematic effects, such as the predicted neutrino interaction cross section, are the main sources of the non-flatness. The best-fit $L/E$ distribution for oscillations, allowing systematic terms to vary within the estimated uncertainty (as described below), also shows this rise with respect to no-oscillation prediction, as seen in the curves overlaid in Fig. 4. The rise at large $L/E$ is consistent with the data.

The observed $L/E$ distribution was fit assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. The $L/E$ distribution was divided into 43 bins from $\log(L/E) = 0$ to 4.3. The likelihood of the fit and the $\chi^2$ were defined as:

$$\mathcal{L}(N^\text{pred}, N^\text{obs}) = \frac{43 \exp \left(-N^\text{pred}_i\frac{N^\text{obs}_i}{N^\text{obs}_i} \right)}{\prod_{j=1}^{24} \exp \left(-\frac{\epsilon_j^2}{2\sigma_j^2} \right)},$$

$$N^\text{pred}_i = N^0_i \cdot P(\nu_\mu \to \nu_\mu) \cdot (1 + \sum_{j=1}^{25} f_j^i, \epsilon_j),$$

$$\chi^2 \equiv -2 \ln \left( \frac{\mathcal{L}(N^\text{pred}, N^\text{obs})}{\mathcal{L}(N^\text{obs}, N^\text{obs})} \right),$$

where $N^\text{obs}_i$ is the number of the observed events in the $i$-th bin and $N^\text{pred}_i$ is the number of predicted events, in which neutrino oscillation and systematic uncertainties are considered. $N^0_i$ is the MC predicted number of events without oscillation for the $i$-th bin. Various systematic uncertainties are represented by 25 parameters $\epsilon_j$, which include 7 uncertainty parameters from the flux calculation (among these, absolute normalization is treated as a free parameter), 3 from the detector calibration and background, 2 from the data reduction, 5 from the event reconstruction, and 8 from the neutrino interaction simulation. A more detailed description of the systematic error terms can be found in Ref. 10. The second term in the likelihood definition represents the contributions from the systematic errors, where $\sigma_j$ is the estimated uncertainty in the parameter $\epsilon_j$. The fractional effect of systematic error term $\epsilon_j$ on the $i$-th bin is given by $f_j^i$.

A scan was carried out on a $(\sin^2 2\theta, \log \Delta m^2)$ grid, minimizing $\chi^2$ by optimizing the systematic error parameters at each point. The minimum $\chi^2$ was 37.9/40 DOF at $(\sin^2 2\theta, \Delta m^2) = (1.00, 2.4 \times 10^{-3} \text{eV}^2)$. Including unphysical parameter region ($\sin^2 2\theta > 1$), the best-fit was obtained at $(\sin^2 2\theta, \Delta m^2) = (1.02, 2.4 \times 10^{-3} \text{eV}^2)$, in which the minimum $\chi^2$ was 0.12 lower than that in the physical region. Figure 4 shows the contour plot of the allowed oscillation parameter regions. Three contours correspond to the 68 $\%, 90 \%$ and 99 $\%$ confidence level (C.L.) allowed regions, which are defined to be $\chi^2 = \chi_{\text{min}}^2 + 2.48, 4.83,$ and 9.43, respectively, where $\chi_{\text{min}}^2$ is the minimum $\chi^2$ in the physical region. These intervals are derived based on a two dimensional extension of the method described in Ref. 17. The 90 $\%$ C.L. allowed parameter region was obtained as $1.9 \times 10^{-3} \text{eV}^2 < \Delta m^2 < 3.0 \times 10^{-3} \text{eV}^2$ and $\sin^2 2\theta > 0.90$. The result
is consistent with that of the oscillation analysis using zenith angle distributions [1, 16].

In order to test the significance of the dip in $L/E$, a null hypothesis that includes the basic shape of the $L/E$ distribution is needed. The no-oscillation case is disfavored more strongly.

In summary, we have studied the survival probability of muon neutrinos as a function of $L/E$ using atmospheric neutrino events observed in Super-Kamiokande. A dip in the $L/E$ distribution was observed around $L/E = 500$ km/GeV. This strongly constrains $\Delta m^2$. Alternative models that could explain the zenith angle and energy dependent deficit of the atmospheric muon neutrinos are disfavored, since they do not predict any dip in the $L/E$ distribution. We conclude that the observed $L/E$ distribution gives the first direct evidence that the neutrino survival probability obeys the sinusoidal function as predicted by neutrino flavor oscillations.

We gratefully acknowledge the cooperation of the Kamioka Mining and Smelting Company. The Super-Kamiokande experiment has been built and operated from funding by the Japanese Ministry of Education, Culture, Sports, Science and Technology, the United States Department of Energy, and the U.S. National Science Foundation.

* Present address: Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA

[1] Y. Fukuda et al., Phys. Rev. Lett. 81, 1562 (1998).
[2] Y. Fukuda et al., Phys. Lett. B335, 237 (1994).
[3] R. Becker-Szendy et al., Phys. Rev. D46, 3720 (1992).
[4] M. Ambrosio et al., Phys. Lett. B343, 451 (1998).
[5] M. Sanchez et al., Phys. Rev. D68, 113004 (2003).
[6] B. T. Cleveland et al., Astrophys. J. 496, 505 (1998).
[7] Y. Fukuda et al., Phys. Rev. Lett. 77, 1683 (1996).
[8] W. Hampel et al., Phys. Lett. B447, 127 (1999).
[9] J. N. Abdurashitov et al., J. Exp. Theor. Phys. 95, 181 (2002).
[10] M. Altmann et al., Phys. Lett. B490, 16 (2000).
[11] M. B. Smy et al., Phys. Rev. D69, 011104 (2004).
[12] S. N. Ahmed et al. (2003), nucl-ex/0309004.
[13] K. Eguchi et al., Phys. Rev. Lett. 90, 021802 (2003).
[14] M. H. Ahn et al., Phys. Rev. Lett. 90, 041801 (2003).
[15] P. C. de Holanda and A. Y. Smirnov (2003), hep-ph/0309299.
[16] Y. Ashie et al. (Super-Kamiokande) (2004), draft in preparation.
[17] R. M. Barnett et al. (Particle Data Group), Phys. Rev. D54, 1 (1996).
[18] V. D. Barger et al., Phys. Rev. D46, 2649 (1992).
[19] V. D. Barger et al., Phys. Lett. B462, 109 (1999).
[20] Y. Grossman and M. P. Worah (1998), hep-ph/9807511.
[21] E. Lisi, A. Marrone, and D. Montanino, Phys. Rev. Lett. 85, 1166 (2000).

![FIG. 5: 68, 90 and 99% C.L. allowed oscillation parameter regions for 2-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations obtained by the present analysis.](image-url)