Atmospheric Neutrinos in Super–Kamiokande

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Since the initial announcement of evidence for oscillations of atmospheric neutrinos [1], Super–Kamiokande has increased its atmospheric neutrino sample by 40% to 45.3 kiloton-years of fully-contained interactions and 42.2 kiloton-years of partially-contained interactions. The data exhibit significantly low values of R ($\equiv (\mu/e)_{DATA}/(\mu/e)_{MC}$) in both the sub-GeV sample ($R = 0.67 \pm 0.02 \pm 0.05$) and multi-GeV sample ($R = 0.66 \pm 0.04 \pm 0.08$) due to a zenith-angle dependent deficit of muon neutrino induced events. The observed deficits cannot be explained by any combination of known systematic uncertainties but are consistent with neutrino oscillations of $\nu_\mu \leftrightarrow \nu_\tau$ with $\sin^2 2\theta > 0.86$ and $1 \times 10^{-3} < \Delta m^2 < 8 \times 10^{-3}$ eV^2. The data are also well fit by oscillations of $\nu_\mu \leftrightarrow \nu_{sterile}$ with $\sin^2 2\theta > 0.87$ and $2 \times 10^{-3} < \Delta m^2 < 7 \times 10^{-3}$ eV^2. With the current sample, these two oscillation modes cannot be distinguished.

I. INTRODUCTION

Atmospheric neutrinos are the decay products of particles produced when cosmic rays strike the upper atmosphere. Neutrinos result mostly from the decay chain of pions, $\pi^+ \to \mu^+\nu_\mu$ followed by $\mu^+ \to e^+\bar{\nu}_\mu\nu_e$, so that the expected ratio of $(\nu_\mu + \bar{\nu}_\mu)$ flux to $(\nu_e + \bar{\nu}_e)$ flux is 2 at neutrino energies of $\sim$1 GeV. While the total neutrino flux is estimated with 20% uncertainty, the ν_μ/ν_e ratio is estimated over a broad range of energies from 0.1 to 10 GeV with only 5% uncertainty [2,3].

The ν_μ/ν_e ratio is measured in underground detectors by observing the final-state charged leptons resulting from neutrino-nucleon interactions, $\nu + N \to l + X$. The flavor of the final-state lepton is used to tag the neutrino flavor. Measurements of the ν_μ/ν_e ratio are reported as $R \equiv (\mu/e)_{DATA}/(\mu/e)_{MC}$, where μ is the number of muon events observed and e is the number of electron events observed in data and a Monte Carlo simulation based on the predicted fluxes. In this ratio, the experimental and theoretical uncertainties largely cancel. If the Monte Carlo simulation accurately describes the data, an R value of 1 is expected.

The early water Cherenkov experiments, IMB [4] and Kamiokande [5], both observed significantly low values of R, although the iron-based detectors Fréjus [6] and NUSEX [7] observed values of R consistent with 1. Recently, the iron-calorimeter experiment, Soudan 2, has reported small value of R [8].

Observations of small R values have been attributed to neutrino oscillations. For two-neutrino mixing the survival probability for a neutrino produced in flavor state α to be observed in the same flavor state after traveling a distance L through the vacuum is:

$$P(\alpha \to \alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right), \tag{1}$$

where E_ν is the neutrino energy, θ is the mass-flavor state mixing angle and Δm^2 is the difference of the mass eigenvalues squared. On average, atmospheric neutrinos produced directly overhead travel 15 km before interacting in the detector while those produced directly below the detector travel 12,700 km. Thus the oscillation probability is a function of the neutrino zenith angle, Θ, which is defined so that vertically down-going neutrinos have $\cos\Theta = 1$, and vertically up-going neutrinos have $\cos\Theta = -1$. The neutrino fluxes are expected to be up-down symmetric at energies above $E_\nu > 3$ GeV where the effects of the Earth's magnetic field on the primary cosmic ray flux are small. In addition to low R values, zenith angle asymmetries in the atmospheric neutrino flux are a signature for neutrino oscillations. Early evidence for an up-down asymmetry of the atmospheric neutrino flux came from the Kamiokande experiment [9].

II. THE SUPER–KAMIOKANDE DETECTOR

Super–Kamiokande (Super–K) is a 50 kilo-ton water Cherenkov detector located in an active zinc mine 1200 m (2700 m water equivalent) underground in Gifu Prefecture, Japan. The water tank is optically separated into two concentric volumes, the inner detector (ID) and the outer-detector (OD). The ID is instrumented with 11,146 20-inch photomultiplier tubes (PMT) facing a 22.5 kiloton fiducial volume. Interaction kinematics of in the ID are reconstructed using both timing and charge information from each PMT. The OD is roughly 2 m thick and is viewed by 1885 8-inch PMT's fitted with 60 cm $\times$ 60 cm waveshifter plates. To further enhance light collection in the OD the walls have been lined with reflective material. The OD is used to veto entering tracks and to tag tracks that exit the inner volume.

III. DATA SAMPLE

Since Super–K's initial announcement of evidence for neutrino oscillations, the experiment has increased its data sample by 40%. The data sample reported here combines a 736-day (45.3 kiloton-year) sample of fully-contained (FC) interactions and a 685-day (42.2 kiloton-year) sample of partially-contained interactions (PC). FC events deposit visible energy only in the ID while PC events have exiting tracks which deposit energy in the OD forming a cluster of OD PMT hits near the exit point.

To select FC neutrino interactions, simple cuts limiting the number of hit tubes in the OD reduce the sample from roughly 1×10^6 events/day to 500 events/day. Further automated cuts are used to remove remaining background from entering cosmic ray muon events and events caused "flashing" PMT's which emit light due to internal corona discharge. The remaining 15 events/day are double scanned by physicists to remove remaining background reducing the final sample to 14 events/day of which 8.3 are in the fiducial volume. Event selection for FC events is estimated to save neutrino interactions with $> 99.9\%$ efficiency.

PC events are selected by requiring only a single cluster of PMT's in the OD. Background from cosmic ray muons is reduced by cuts which identify if the OD cluster was caused by a particle entering or exiting the ID. Of the 1×10^6 triggers recorded each day, the PC event selection reduces the sample to 2 events/day. These events are double scanned by physicists to remove remaining backgrounds from cosmic ray muons. The final sample contains roughly 0.8 events/day of which 0.5 are in the fiducial volume. The efficiency to save PC neutrino interactions is estimated to be $88 \pm 5\%$ [10].

To keep pace with the increase in data size, the previous 10-year equivalent Monte Carlo sample was replaced with a new 20-year equivalent sample. For the new sample, the calculations of the deep-inelastic neutrino-nucleus cross sections were updated to use GRV94 [11] parton distribution functions. This change resulted in approximately a 2% increase in the predicted single-ring rates over the previous estimates. Also, since Super–K began at a low point in the solar cycle, we have assumed solar minimum neutrino fluxes in the current Monte Carlo calculation. This also results in an approximate 2% increase in the predicted sub-GeV single-ring rate relative to the previous estimates based on solar average neutrino fluxes.

TABLE I. Summary of the event rates and R values for the sub-GeV and multi-GeV + PC samples. Monte Carlo expectation has been normalized to the data livetimes (736 days FC, 685 days PC). For the calculation of the multi-GeV R value, the PC events have been scaled to the livetime of the FC events.

	sub-GeV		multi-GeV	
	Data	Monte Carlo	Data	Monte Carlo
single-ring	3224	3788.3	687	773.3
e-like	1607	1510.5	386	357.4
μ-like	1617	2277.8	301	415.9
multi-ring	1271	1614.2	737	925.6
total	4495	5402.5	1424	1698.9
partially-contained			374	528.7
	$R = 0.67 \pm 0.02(stat.) \pm 0.05(sys.)$		$R_{FC+PC} = 0.66 \pm 0.04(stat.) \pm 0.08(sys.)$	

Table I summarizes the number of events observed in the sub-GeV ($p_e > 100$ MeV/c, $p_\mu > 200$ MeV/c, $E_{vis} <$ 1.33 GeV) and multi-GeV ($E_{vis} > 1.33$ GeV and PC events) energy ranges as well as the predicted number of events based on a Monte Carlo calculation using neutrino fluxes from Ref. [3]. In both the sub-GeV and multi-GeV samples significantly low R values are observed. We estimate the probability that these measurements are due to a fluctuation to be less than 0.001% for the sub-GeV sample and less than 1% for the multi-GeV sample.

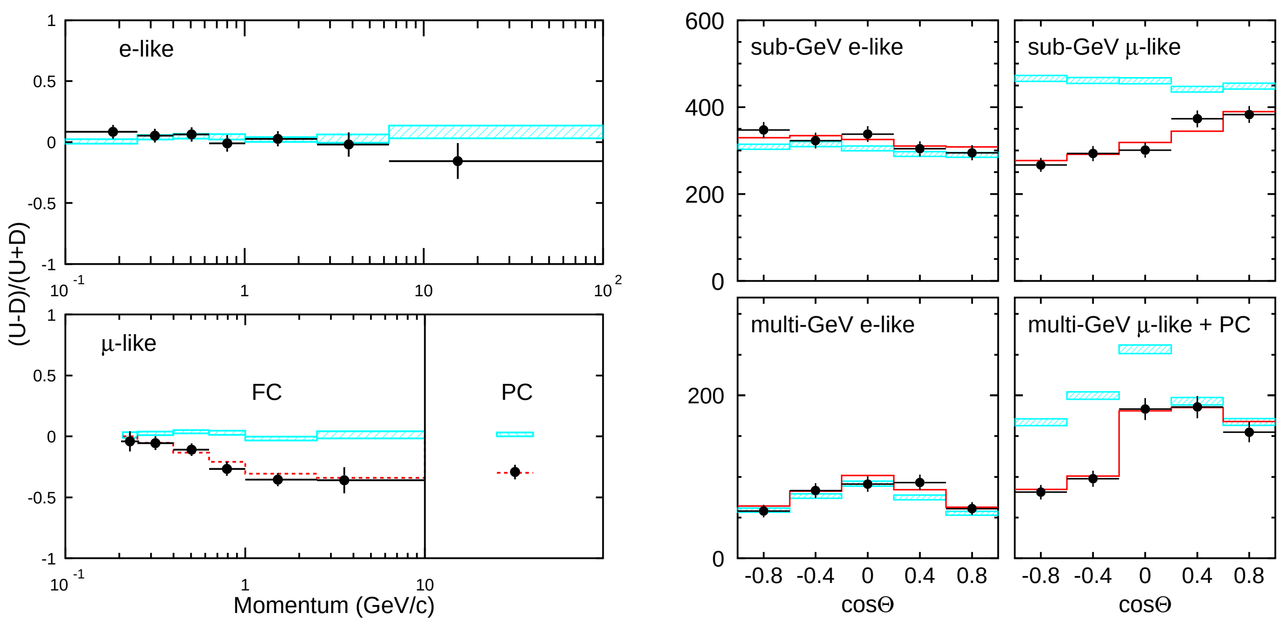

FIG. 1. Left: The (U-D)/(U+D) zenith angle asymmetry for e-like and μ-like events versus momentum. Hatched region shows the prediction for no oscillations combining systematic and Monte Carlo statistical errors in quadrature. The expectation for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\sin^2 2\theta = 1$ and $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2 is shown by the dashed line. Right: Event rates for the sub-GeV and multi-GeV+PC samples. The expected rates for no neutrino oscillations is shown in hatched region with Monte Carlo statistical errors. Expectation for oscillations of $\nu_\mu \leftrightarrow \nu_\tau$ with $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2 is shown by the solid line.

The muon neutrino deficit exhibits a significant zenith angle dependence. The asymmetry is defined as: $A = (U - D)/(U + D)$, where U is the number of upward-going events ($\cos\Theta < -0.2$) and D is the number of downward-going events ($\cos\Theta > 0.2$). Figure 1 plots the zenith angle asymmetry versus reconstructed lepton momentum. While the behavior of the e-like asymmetry is consistent with expectations, the observed asymmetry for the μ-like events grows with momentum. Considering the multi-GeV μ-like event alone the measured asymmetry,

$$A = -0.311 \pm 0.043 \pm 0.010, \tag{2}$$

differs from 0 by more than 7 standard deviations. Figure 1 also shows the expected and measured zenith angle event rates for the sub-GeV and multi-GeV samples. Both the sub-GeV and multi-GeV μ-like samples show a significant zenith angle distortion.

This zenith angle asymmetry cannot be explained by the effects of the Earth's magnetic field on cosmic rays as these effects are only important for $E_\nu < 3$ GeV. Further, Super–K has recently measured the predicted east-west asymmetry in the neutrino flux [12]. This measurement is largely insensitive to neutrino oscillations, and has been found to be consistent with expectations. The measured agreement between the data and the predicted azimuthal neutrino distributions indicates that geomagnetic effects are adequately modeled in the neutrino flux calculations and demonstrates Super–K's ability to resolve angular distortions in the atmospheric neutrino rates.

The observed muon neutrino deficits have been analyzed in the context of two-component neutrino oscillations. To estimate the oscillation parameters, $\sin^2 2\theta$ and Δm^2, a χ^2 is defined:

$$\chi^2 = \sum_{cos\Theta,p} (N_{DATA} - N_{MC})^2/\sigma^2 + \sum_j \epsilon_j^2/\sigma_j^2, \tag{3}$$

where the first sum is over 70 bins ($e, \mu \times 7$ bins in momentum $\times$ 5 bins in $\cos\Theta$) and the second sum is over the Monte Carlo parameters $\epsilon_j = (\delta, \beta_s, \beta_m, \rho, \eta_s, \eta_m, \lambda)$. These parameters adjust the Monte Carlo event rate estimates for uncertainties in the neutrino spectrum power-law, the sub-GeV μ/e ratio, the multi-GeV μ/e ratio, the relative normalizations of the fully- and partially-contained samples, the sub- and multi-GeV zenith angle distributions, and the average ratio of L/E_ν. The meanings and estimated uncertainties of these parameters are summarized in Table II.

When the data are analyzed assuming no oscillations ($\sin^2 2\theta = 0, \Delta m^2 = 0$), a minimum χ^2 of 175/69 DoF, $P < 0.0001\%$, is obtained. The best fit for two-flavor neutrino oscillations of $\nu_\mu \leftrightarrow \nu_e$ is also poor, $\chi^2_{min} = 110/67$ DoF, $P < 0.1\%$. In simulations of $\nu_\mu \leftrightarrow \nu_e$ the effects of matter on neutrino propagation through the Earth have been treated following Refs. [13,14].

TABLE II. Summary of Monte Carlo fit parameters. Estimated uncertainties and best-fit values for $\nu_\mu \leftrightarrow \nu_\tau(\Delta m^2 = 3.5 \times 10^{-3}\text{eV}^2,\ \sin^2 2\theta = 1.0)$ and estimated uncertainties are given.

	Monte Carlo Fit Parameters	Best Fit	Uncertainty
α	overall normalization	15.8%	-[a]
δ	E_ν spectral index	0.006	$\sigma_\delta = 0.05$
β_s	sub-GeV μ/e ratio	-6.3%	$\sigma_s = 8\%$
β_m	multi-GeV μ/e ratio	-11.8%	$\sigma_m = 12\%$
ρ	relative norm. of PC to FC	-1.8%	$\sigma_\rho = 8\%$
λ	L/E_ν	3.1%	$\sigma_\lambda = 15\%$
η_s	sub-GeV up-down	2.4%	$\sigma_\eta^s = 2.4\%$
η_m	multi-GeV up-down	-0.09%	$\sigma_\eta^m = 2.7\%$

[a]The over-all normalization (α) was estimated to have a 25% uncertainty but was fitted as a free parameter.

The data are well fit, however, by neutrino oscillations of $\nu_\mu \leftrightarrow \nu_\tau$ and oscillations of $\nu_\mu \leftrightarrow \nu_{sterile}$. The best-fit for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations is obtained at ($\sin^2 2\theta = 1.0, \Delta m^2 = 3.5 \times 10^{-3}$ eV^2 with $\chi^2_{min} = 62.1/67$ DoF, $P = 65\%$. The best-fit assuming $\nu_\mu \leftrightarrow \nu_{sterile}$ is comparable, $\chi^2_{min} = 64.3/67$ DoF, $P = 57\%$. With the current data sample oscillations of ν_μ to ν_τ cannot be distinguished from oscillations of $\nu_\mu \leftrightarrow \nu_{sterile}$. The best-fit values of the Monte Carlo parameters at the minimum for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations are summarized in Table II.

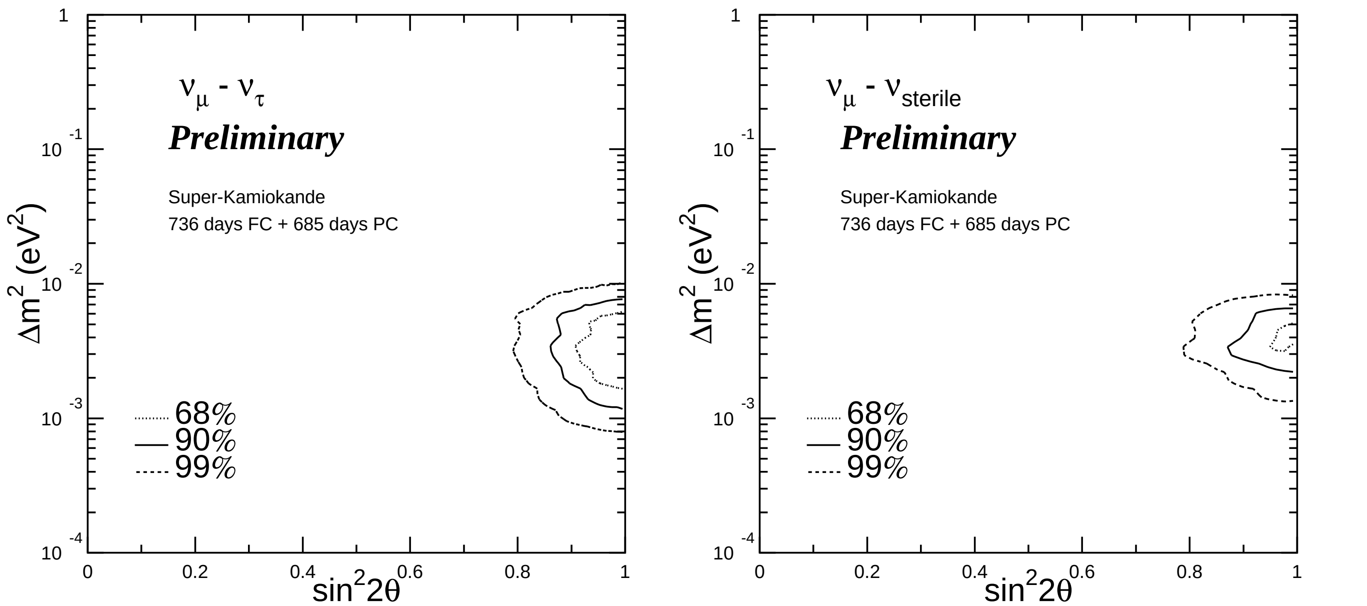

FIG. 2. The 68%, 90%, and 99% confidence intervals are shown for $\sin^2 2\theta$ and Δm^2 under the assumption of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations and $\nu_\mu \leftrightarrow \nu_{sterile}$ oscillations.

The confidence intervals for the oscillation parameters $\sin^2 2\theta$ and Δm^2 for both cases are shown in Fig. 2. Similar confidence intervals were estimated using the Unified Approach [15]. Note that at the lowest values of Δm^2 allowed for the $\nu_\mu \leftrightarrow \nu_\tau$ hypothesis, suppression of the effective mixing angle due to matter effects reduces the quality of the $\nu_\mu \leftrightarrow \nu_{sterile}$ fit. Significantly, the 90% C.L. contours do not extend below $\Delta m^2 = 10^{-3}$ eV^2 indicating that oscillation signals are likely to be observed by the long-baseline experiments K2K and MINOS.

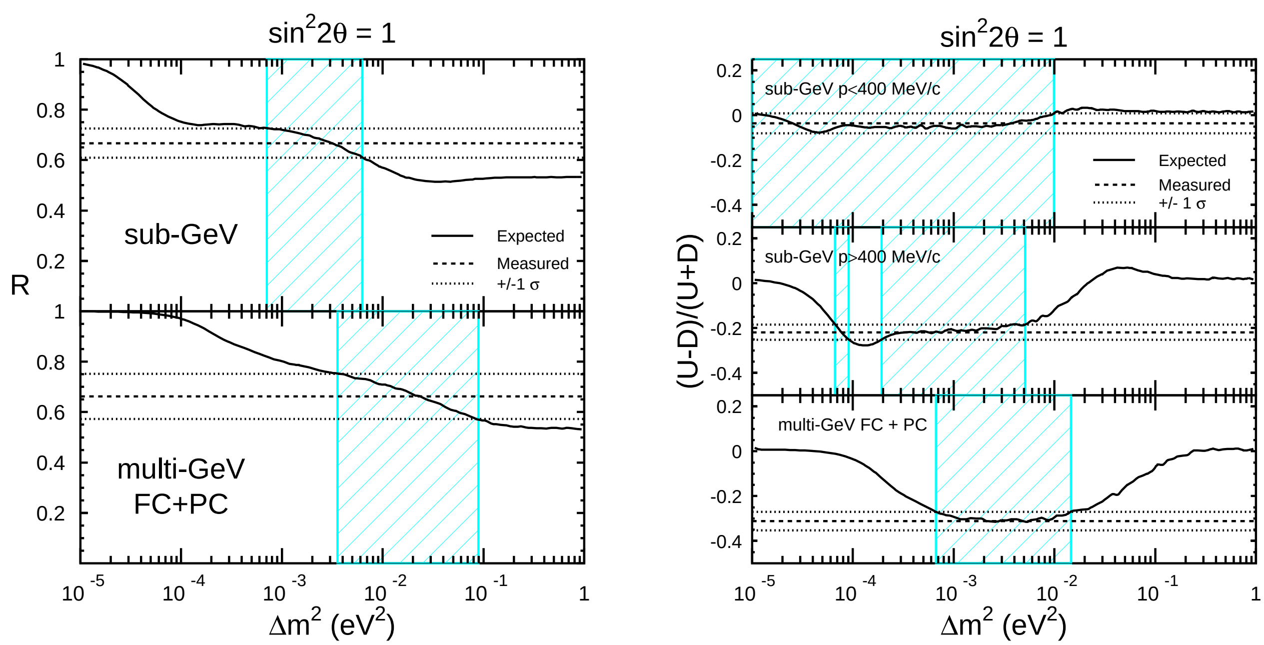

FIG. 3. Left: The expected value of R for the sub-GeV and multi-GeV samples is shown as a function of Δm^2 with fixed $\sin^2 2\theta$=1. The measured R values are shown with $\pm 1\sigma$ errors. Right: The zenith angle asymmetries, A, are plotted for the sub-GeV, $p > 400$ MeV/c, sub-GeV ($p < 400$ MeV/c) and multi-GeV samples.

As a cross-check of the above analysis we have analyzed both signatures of neutrino oscillations, the μ/e "double-ratio", R, and the zenith angle asymmetry, A, separately. Figure 3 shows the expected values of R for the sub-GeV and multi-GeV samples as a function of Δm^2 holding $\sin^2 2\theta$ fixed at 1. The measured R values for these samples prefer the range $3\times10^{-3} < \Delta m^2 < 6\times10^{-3}$ eV^2. Also plotted in Fig. 3 are the expected zenith angle asymmetries, A, for the sub-GeV ($p < 400$ MeV/c and $p > 400$ MeV/c separately), and the multi-GeV samples as functions of Δm^2 holding $\sin^2 2\theta$ fixed at 1. The measured zenith angle asymmetries prefer the range $7\times10^{-4} < \Delta m^2 < 5\times10^{-3}$ eV^2 in good agreement with the measured R values.

IV. CONCLUSIONS

Super–Kamiokande has collected and analyzed 736 days (45.3 kiloton-years) of fully-contained atmospheric neutrino interactions and 685 days (42.2 kiloton-years) of partially-contained atmospheric neutrino interactions. In this data, a significant deficit of ν_μ-induced interactions is observed which varies with zenith angle. While no known combination of theoretical and experimental uncertainties can explain these deficits, the data are well modeled by neutrino oscillations of $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_{sterile}$. Based on an analysis of the momentum and zenith angle distribution of the events, the 90% allowed ranges of oscillation parameters are $\sin^2 2\theta > 0.86$, $1\times10^{-3} < \Delta m^2 < 8\times10^{-3}$ eV^2 assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, and $\sin^2 2\theta > 0.87$, $2\times10^{-3} < \Delta m^2 < 7\times10^{-3}$ eV^2 assuming $\nu_\mu \leftrightarrow \nu_{sterile}$ oscillations. With the current sample these two oscillations modes cannot be distinguished.

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