



## Search for Diffuse Astrophysical Neutrino Flux with Super-Kamiokande

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**Abstract:** Many astrophysical models predict a diffuse flux of high-energy neutrinos from active galactic nuclei and other extra-galactic sources. We have performed a search for this astrophysical neutrino flux by looking for upward-going muons in the highest energy data sample from the Super-Kamiokande detector. We found one extremely high energy upward-going muon event, compared with an expected background of  $0.46 \pm 0.23$  events. Using this result, we set an upper limit on the diffuse flux of upward-going muons due to neutrinos from astrophysical sources in the muon energy range 3.16–100 TeV.

### Introduction

Many astrophysical phenomena are expected to produce GeV-PeV neutrinos, such as active galactic nuclei (AGNs) and gamma-ray bursts (GRBs) [4]. Such neutrinos can be observed via muons produced by  $\nu_\mu$  or  $\bar{\nu}_\mu$  interacting in the Earth that travel upwards through an underground detector. At muon energies above  $\sim 10$  TeV, the upward-going muon flux due to neutrinos from AGNs is expected to exceed the flux due to atmospheric neutrinos [9, 8] and could potentially be observed as an excess diffuse flux in this energy range.

Here we present a search for such a flux using the Super-Kamiokande (Super-K) detector [3], a 50 kiloton water Cerenkov detector consisting of a cylindrical inner detector (ID) instrumented with inward-facing photomultiplier tubes (PMTs) and an outer detector (OD), which is a cylindrical shell of water surrounding the ID instrumented with outward-facing PMTs. The data sample used in this analysis, SK-I, was taken from 1996 April to 2001 July, with 1679.6 days of detector livetime.

### Observed flux

The highest energy sample in SK-I consists of events that deposit  $\geq 1.75 \times 10^6$  photoelectrons (pe) in the ID. At this high-pe threshold, the ID PMT electronics are saturated, so these extremely

energetic events are not included in other SK-I studies. Our search for a high-energy astrophysical neutrino flux analyzes this ultra-high-energy sample separately using an OD-based fitting method.

To select candidate upward-going muons, we applied a simple linear fit to the OD data for each event. A linear fit was done on the  $z$ -position of each OD PMT versus the time it fired, weighted by the total charge in the PMT. Example fits of simulated events are shown in Figure 1. A similar linear fit was done on the  $x$ - and  $y$ -positions to determine the full muon trajectory through the detector.

Based on this trajectory, we applied automated cuts to select candidate upward-going muons. After applying these cuts to the 52214 events in the ultra-high-energy sample, 343 candidate events remained. These remaining events were then evaluated by a visual scan and a manual direction fit, leaving one event selected as being truly upward-going. This event is the ultra-high energy upward-going muon signal observed by SK-I. It occurred on 2000 May 12 at 12:28:07 UT and came from the direction of (R.A., decl.) =  $20^{\text{h}}38^{\text{m}}, -37^{\circ}18'$ .

The flux of upward-going muons above a threshold energy  $E_\mu^{\text{min}}$  is given by

$$\Phi_\mu (\geq E_\mu^{\text{min}}) = \frac{1}{2\pi T k (\geq E_\mu^{\text{min}})} \times \sum_{j=1}^n \frac{1}{\varepsilon (\geq E_\mu^{\text{min}}, \Theta_j) A(\Theta_j)}, \quad (1)$$

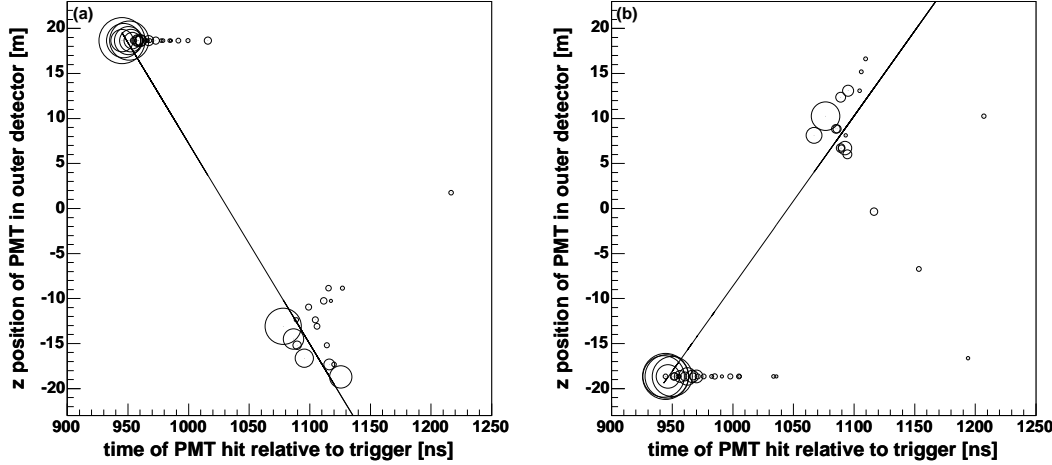


Figure 1: (a) OD-based muon trajectory fit applied to an example MC downward-going muon event. (b) OD-based fit applied to an example MC upward-going muon event. The size of the circle around each point is proportional to the charge detected in the PMT.

where  $n$  is the total number of upward-going muon events observed and  $\Theta_j$  is the zenith angle of the  $j$ th event.  $T$  is the detector livetime and  $A(\Theta_j)$  is the effective area of the detector. The efficiency  $\varepsilon(\geq E_\mu^{\min}, \Theta_j)$  of our data reduction on upward-going,  $\geq 1.75 \times 10^6$  pe muons and the probability  $k(\geq E_\mu^{\min})$  that a muon with energy above the threshold will deposit  $\geq 1.75 \times 10^6$  pe in the ID were determined using a high-energy isotropic Monte Carlo (MC) sample consisting of an isotropic flux of muons in seven monoenergetic bins with muon energies ranging from 0.1–100 TeV.

Equation (1) was applied to the detected upward-going muon event to calculate  $\Phi_\mu(\geq E_\mu^{\min})$ . Results are shown in Table 1. The dominant sources of uncertainty are systematic uncertainties on the efficiency and statistical uncertainties from the MC. This flux includes both the potential signal from astrophysical neutrinos and the atmospheric neutrino background.

## Expected background

The dominant background for an astrophysical neutrino search is the atmospheric neutrino spec-

$E_\mu^{\min}$ (TeV)	$\Phi_\mu(\geq E_\mu^{\min})$ ( $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ )	
3.16	$2.64 \times 10^{-14}$	+16.1%
		-17.9%
10	$8.23 \times 10^{-15}$	+9.48%
		-9.73%
31.6	$3.25 \times 10^{-15}$	+6.67%
		-6.40%
100	$1.10 \times 10^{-15}$	+4.96%
		-4.09%

Table 1: The flux of ultra-high energy upward-going muons as observed by SK-I.

trum produced by pion and kaon decays from cosmic ray interactions in the atmosphere. We have used an atmospheric neutrino MC [2] simulating 100 yr of atmospheric neutrino flux as modeled in [6, 11] up to neutrino energies of 100 TeV.

We applied the same data reduction to this MC that we applied to the SK-I data. A total of 11 MC events passed our data reduction as being ultra-high-energy upward-going muons. Out of these 11, three originate from a region covered twice and is thus divided in half, giving 9.5 MC events in 100

yr. Scaling to SK-I's live time gives an expected background of  $0.44 \pm 0.22$  events. (The statistical uncertainty is 31%, and the systematic uncertainties total 40%, giving a total uncertainty of 50%.)

We adjusted this estimate by performing an analytical calculation of the expected flux to account for effects not included in the atmospheric MC: neutrinos over 100 TeV, attenuation of neutrinos passing through the Earth and the ‘‘prompt’’ atmospheric neutrino flux from decays of short-lived charmed particles from cosmic ray interactions [5].

The flux of muons  $\Phi_\mu (\geq E_\mu^{\min})$  above an energy threshold  $E_\mu^{\min}$  is given by

$$\Phi_\mu (\geq E_\mu^{\min}) = \int_{E_\mu^{\min}}^{\infty} dE_\nu P_\mu (E_\nu, E_\mu^{\min}) \frac{d\Phi_\nu^{\text{av}} (E_\nu)}{dE_\nu}, \quad (2)$$

where  $P_\mu (E_\nu, E_\mu^{\min})$  is the probability that an incoming neutrino with energy  $E_\nu$  will produce a muon with energy above the threshold  $E_\mu^{\min}$  at the detector, and  $d\Phi_\nu^{\text{av}} (E_\nu)/dE_\nu$  is the differential neutrino flux averaged over solid angle and reduced by an exponential factor due to attenuation of the neutrinos as they pass through the Earth.

The expected number of events  $N$  seen by Super-K in livetime  $T$  is given by

$$N = 2\pi T A_{\text{av}} \times \int_0^\infty dE_\mu^{\min} \frac{d\Phi_\mu (\geq E_\mu^{\min})}{dE_\mu^{\min}} k (E_\mu^{\min}) \quad (3)$$

where  $d\Phi_\mu (\geq E_\mu^{\min})/dE_\mu^{\min}$  is the derivative of the curve calculated by equation (2) and  $k (E_\mu^{\min})$  is the fraction of muons with energy above  $E_\mu^{\min}$  that will deposit  $\geq 1.75 \times 10^6$  pe in the ID.

We used equation (3) to calculate correction factors for the effects not included in the atmospheric MC. After applying these corrections, our final estimate of the background is  $0.46 \pm 0.23$  events.

This atmospheric background comes from a lower energy range than the range expected for an astrophysical neutrino signal. Since there are many more low-energy events in the atmospheric spectrum, they dominate the background even though each one only has a tiny probability of depositing a large amount of energy in the detector.

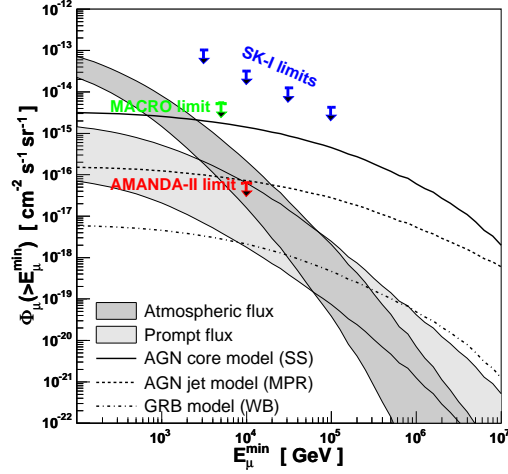


Figure 2: Upper limits from SK-I on muon ( $\mu^+ + \mu^-$ ) flux above energy threshold  $E_\mu^{\min}$ , compared to model fluxes (referenced in text).

## Results

Using the observed ultra-high-energy upward-going muon signal of 1 event and the expected atmospheric neutrino background of  $0.46 \pm 0.23$  events, we have calculated 90% confidence upper limits for the upward-going muon flux in the 3.16 – 100 TeV range due to neutrinos from astrophysical sources (or any other non-atmospheric sources). These limits incorporate both the uncertainty on the background estimate and the uncertainties on the observed flux shown in Table 1.

The results are plotted in Figure 2, along with models of possible signals from AGNs (SS [9] and MPR [8]) and GRBs (WB [12]) and the atmospheric [6, 11] and prompt [5] neutrino backgrounds. Also shown are the limits on a hypothetical  $E_\nu^{-2}$  isotropic neutrino flux set by MACRO [1] and AMANDA-II [7]. The model neutrino fluxes were converted into muon fluxes using equation (2).

We have also converted our limits on the muon flux into approximate limits on the neutrino flux, assuming an  $E_\nu^{-2}$  model neutrino flux. These limits are plotted in Figure 3. Note that converting from

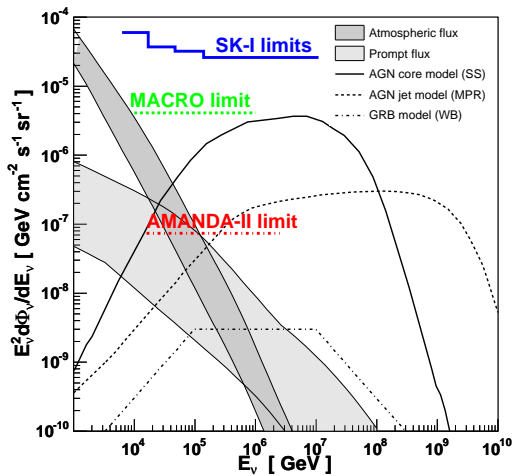


Figure 3: Approximate upper limits from SK-I on astrophysical neutrinos ( $\nu_\mu + \bar{\nu}_\mu$ ). Models shown are the same as in Figure 2.

a muon flux limit to a neutrino flux limit requires additional assumptions and approximations.

## Conclusions

We have developed a method for analyzing Super-K's highest energy data to search for a high-energy neutrino flux from astrophysical sources and studied its efficiency and expected backgrounds. Applying this method to the SK-I data sample does not show evidence of a high-energy cosmic neutrino signal. We have set upper limits on the muon flux due to cosmic neutrino sources which are consistent with the results of other experiments [1, 7]. See [10] for further details on this analysis.

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