A Comparison of Event-Fitting Algorithms for Muons in Super Kamiokande

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Abstract

Super Kamiokande collects data on neutrino flux as a function of zenith angle from the leptons produced by neutrinos. Since the direction of the leptons is only equivalent to the direction of neutrinos if the leptons are above a certain energy threshold, knowing the energy of the leptons is crucial. Track length is the best available estimate of energy. This paper compares track length estimates of several algorithms for stopping muon events.

I. Introduction

Neutrino oscillations

If neutrinos have mass, they have to oscillate between flavors because the eigenstates of flavor and mass are not the same. In interactions we observe neutrinos of definite flavor – it takes a muon neutrino to produce a muon, for instance – but neutrinos propagate according to their mass states, with different mass states having different velocities. The probability that a neutrino which starts out in a flavor eigenstate will oscillate into another flavor eigenstate is given by P_{osc}:

$$P_{osc} = \sin^2 2\text{è} \; \sin^2\left(\frac{1.27\,\Delta m^2\, L}{E}\right),$$

where L is the distance the neutrino traveled (in km), E is its energy (in GeV), θ is the mixing angle and Δm^2 is the difference of the squares of the masses of the flavor states.

Atmospheric neutrinos

When protons in cosmic rays collide with particles in the Earth's upper atmosphere they produce pions and kaons. Atmospheric electron and muon neutrinos (denoted by ν_e and ν_μ) are produced in the decay of charged pions. The reactions are as follows:

$$\text{ð}^+ \rightarrow \text{ì}^+ + \text{í}_{\text{ì}}, \qquad \text{ì}^+ \rightarrow e^+ + \bar{\text{í}}_{\text{ì}} + \text{í}_e;$$

and

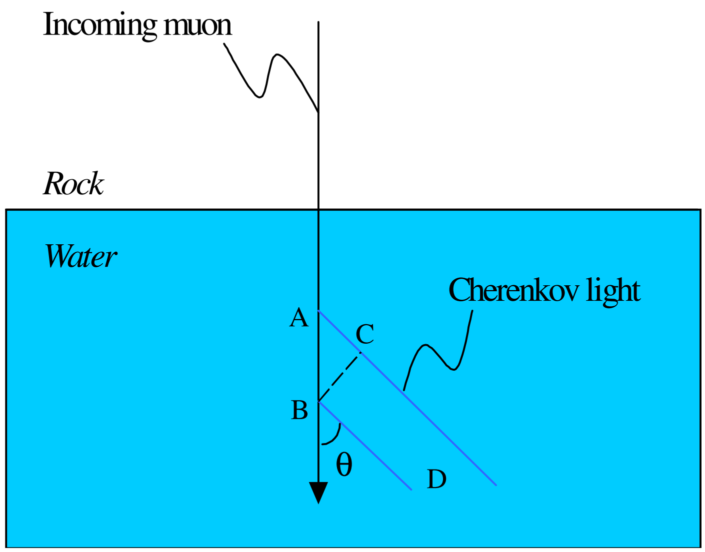
$$\text{ð}^- \rightarrow \text{ì}^- + \bar{\text{í}}_{\text{ì}}, \qquad \text{ì}^- \rightarrow e^- + \text{í}_{\text{ì}} + \bar{\text{í}}_e.$$

This tells us that the flux of muon neutrinos should be twice greater than the flux of electron neutrinos. Since cosmic rays are not affected by the Earth's magnetic field, these reactions take place isotropically. To reach the detector, particles travel a distance L which varies between 20 km and 13,000 km, depending on the particle's zenith angle θ_Z. If neutrinos have mass, their fluxes depend on θ_Z.

As neutrinos travel through the Earth to reach the detector they occasionally collide with nuclei. If the neutrino has sufficient energy, this interaction produces another nucleus and a muon (if it's a muon neutrino) or an electron (if it's an electron neutrino). Super-K measures the number of neutrinos by detecting their leptons. But pion decay produces muons, which can travel tens of kilometers, and it is impossible to distinguish them from the muons produced by neutrino interactions. Luckily, the cosmic ray muons do not have sufficient energies to penetrate larger distances, so all of the upward-going muons detected in Super Kamiokande must come from neutrino interactions. Downward-going muons come predominantly from cosmic rays, therefore, they are not used in analyzing neutrino flux.

II. Detecting Muons

Super-Kamiokande detects muons by measuring the Cherenkov light they produce. Cherenkov radiation was discovered in 1934 by Pavel Cherenkov. It occurs when a charged particle moves faster than the speed of light in a medium. Cherenkov light is emitted in all directions but it is only observed at special angles due to constructive interference.

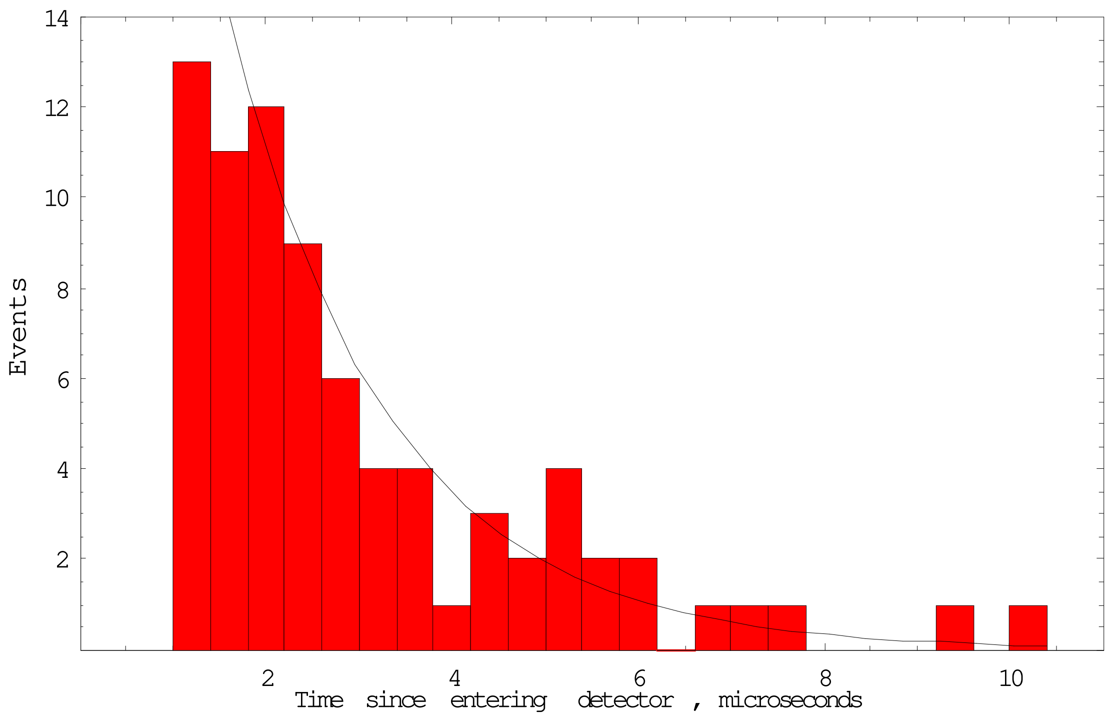


Constructive interference occurs if the muon reaches point B from point A in the same amount of time it takes light to travel from A to C. Since the muon travels at the speed of light in vacuum and Cherenkov light travels at the speed of light in water, we have $\frac{AB}{c} = \frac{AC}{c/n}$, where n is the index of refraction. From the diagram we have $\cos è = \frac{AC}{AB} = \frac{1}{n}$. The index of refraction of Super-K water is 1.395, so the angle between Cherenkov light and the path of the particle is 44°.

III. Finding a Stopping Muon

We used two algorithms, Muboy and Stopmu1st, to find potential stopping muons. Muboy classifies an event as stopping if the number of photoelectrons detected per meter of track length drops by more than forty percent. Muboy selected 221 events as stopping, but it missed 25 events. Stopmu1st classifies all muon events that are not through-going to be stopping muons. Out of 319 events that Stopmu1st selected as stopping, only 156 actually were stopping. Human scanning was used to decide which of the events are truly stopping events. Finally, only events with decay electrons were chosen in order to use decay-electron fitters as well as muon ones.

To make sure that the events we selected were really decaying muons we studied the time distribution of the electrons. The median time between detecting a particle and detecting its decay electron was found to be 3 ± 1 microseconds, which is consistent with the muon's half-life of 2.2 microseconds.



IV. Muon Track Lengths

At first glance it seems plausible that the amount of light deposited by a muon should be an accurate measure of the muon's energy. But because the detector is so large, significant amount of light is absorbed if the muon travels far away from the photomultiplier tubes (PMT's). Therefore, a highly energetic muon moving close to the center of the detector can deposit less light into the PMT's than a muon which has less energy but travels close to the wall.

It is important to know the track length of a muon because if the track length is less than seven meters, the direction of the parent neutrino differs a great deal from the direction of the muon. For muons with track lengths of seven meters or more, the direction of the muon is within one degree of the direction of the parent neutrino. Knowing the track length more precisely allows to use more data in analysis. To find the track length we fit Cherenkov light patterns using several computer programs – Muboy, Hayai, and Kaifit, as well as human fits and a raw-energy estimate.

V. Event-Fitting Algorithms

Muboy

Muboy program, written by Robert Svoboda, can classify and fit stopping, through-going and multiple muon events. The algorithm starts by eliminating some of the background by requiring each photomultiplier tube (PMT) to have a minimum charge and a minimum number of "hit" neighbors. It then chooses the entry point to be the location earliest hit PMT and the entry time to be the time the PMT was hit. Muboy guesses the direction of the track to be towards a patch of 9 neighboring PMTs with the highest charge. It then varies direction and time to maximize *goodness of fit*.

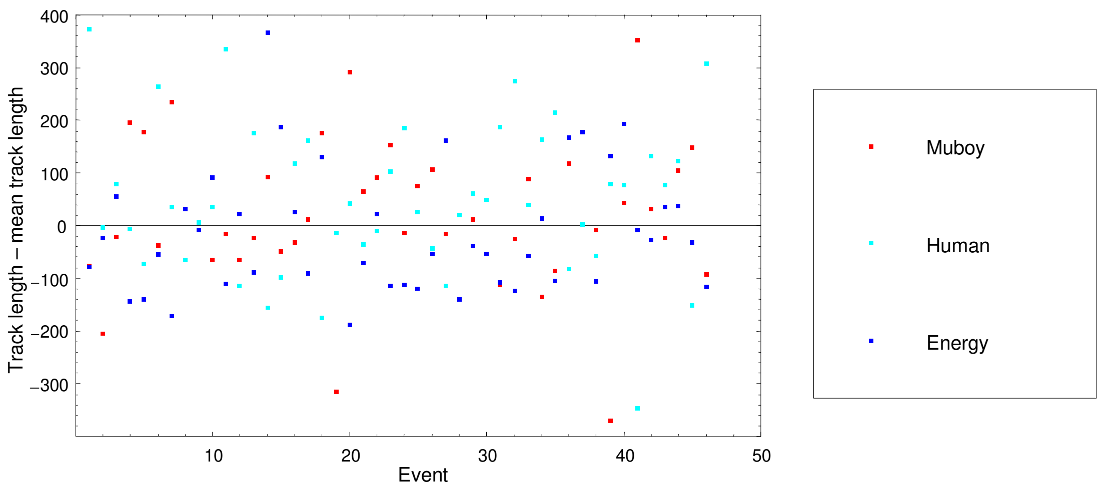
To calculate the goodness of fit Muboy first finds the distribution of times of PMT hits that would be observed if the particle entered at the vertex point that Muboy calculated and stopped at the calculated stopping point. Goodness of fit is a parameter that represents how close this predicted distribution is to the experimental values.

Kaifit Algorithm

Created by Kai Martens, Kaifit identifies and fits decay electrons from muons. Kaifit calculates the position of a decay electron, which, combined with Muboy data gives another estimate of muon track length. Since the muons that decay within the fiducial volume are at least 2 meters away from the walls of the detector, Kaifit cannot simply use the first hit PMT as a vertex point. Instead, it chooses a 200-nanosecond time window with the greatest number of hit PMTs and then picks a narrower time window which maximizes the signal to noise ratio inside the wider time window. It then makes a lattice in the inner detector and finds the point *P* on the lattice that gives the highest goodness of fit. Starting at *P*, the algorithm keeps searching for the point with the highest goodness of fit by creating a smaller grid around *P*. The process is repeated until grid size reaches 5 centimeters. Hayai, another decay electron fitter, performs a spherical grid search instead of using a rectangular grid.

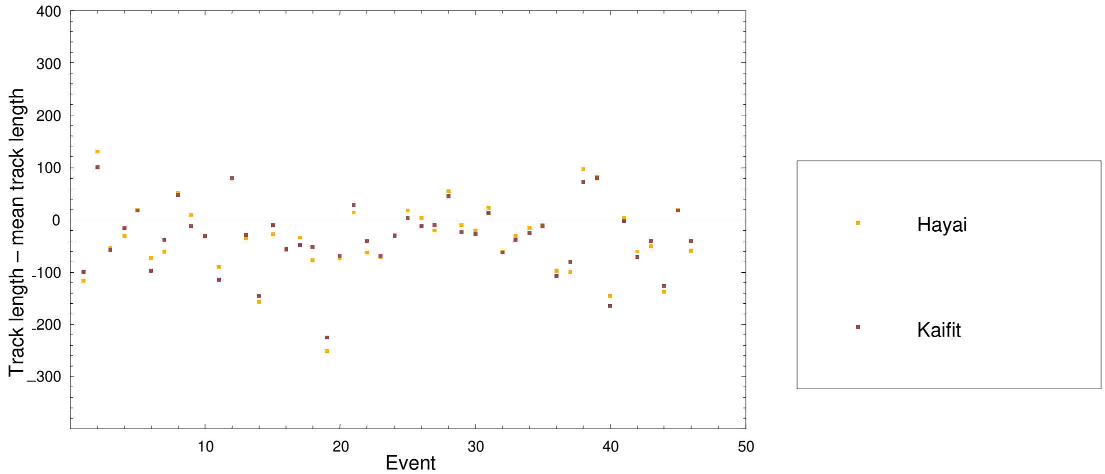
VI. Comparison of Results

Out of 156 events that were identified as stopping muons by hand, 71 had decay electrons. Of these, 46 had Hayai and Kaifit results that were within 30 centimeters of each other, which means that the fits could be good. The results from the five methods of computing track length were compared by subtracting the mean track length for the event from the track length predicted by each algorithm. (See figure below.)



Muboy, human and energy predictions all had a large spread. Muboy and human fits often overestimated the track length while the energy estimate was more often too low. We found that 20.3 photoelectrons per centimeter was a better fit than the 22 PE/cm usually used.

Kaifit and Hayai yielded predictions closest to the mean for most events. (See figure below.) It appears that these two algorithms give the best fits but, unfortunately, they cannot be used in half of muon events because a muon has a fifty percent chance of being absorbed into a nucleus and not having a decay electron.



Further work is needed to learn which track length algorithm works best. By running the algorithms on Monte Carlo data, where the vertex and stopping points are known, we can get a better idea of which algorithm is more accurate.

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