Study of Upward Showering Muons in Super-Kamiokande

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Abstract

A small subset of neutrino-induced upward going muons in the Super-Kamiokande detector consists of high energy muons that undergo radiative energy losses through bremsstrahlung, pair production and photo-nuclear interactions. The mean energy of the parent neutrinos of these showering upward muons is approximately 1 TeV, allowing the selection of a high energy sample of neutrinos. We present the energy spectrum of the parent neutrinos of these upward showering muons and results based on searches for WIMP-induced neutrinos using these upward showering muons are presented.

1. Introduction

Energetic atmospheric neutrinos interact in the rock below the Super-Kamiokande detector and produce two categories of upward muons : upward through going muons which are energetic enough to cross the entire detector and upward stopping muons which decay inside the detector [2]. The energy of the parent neutrinos of the upward stopping and upward thrugoing muons is peaked at around 10 GeV and 100 GeV respectively [3].

Below about 100 GeV the dominant energy loss for the muon is by ionization. However, at very high energies, muons mainly lose energy through radiative processes like Bremsstrahlung, photo-nuclear interaction and e^+e^- pair-production [1]. In water, the critical energy of a muon (where radiative and ionization energy losses are equal) is ~ 1 TeV [4]. We have reconstructed a sample of upward thrugoing muons which undergo radiative energy losses inside the detector which we refer to as "upward showering muons". This sample represents the highest energy neutrinos seen in Super-Kamiokande and is well suited for astronomy studies since the atmospheric neutrino background is lower at high energies. In the next section, we present the algorithm used for isolating the upward showering muons.

2. Method used for identifying showering muons

A normal ionizing muon emits constant amount of Cherenkov light per unit track length. However, for a muon which undergoes radiative energy losses, the generated photons further produce electron -positron pairs thus increasing the total Cherenkov light in the detector. Thus, if we can calibrate the total Cherenkov light emitted by a normal ionizing muon (after accounting for the various sources of light attenuation) in Super-K, then any electromagnetic shower associated with the muon will emit excess light over this amount and this event would be classified as a showering muon.

Given the muon entry point and direction we apply the following correction to the raw charge of each PMT :

$$Q_{corr} = K \frac{Q d_w e^{\left(\frac{d_w}{L_{wt}}\right)}}{F(\theta)} \tag{1}$$

where Q is the photo-electrons detected by each PMT; d_w is the distance traveled by the photons from the point along the muon track where the photon is emitted to the PMT which detects it; $F(\theta)$ is the PMT angular acceptance and shadowing; L_{wt} is the measured water-transparency; and K is an arbitrary normalization constant. To develop an algorithm and test its efficiency we generated 150 muon events for each muon energy where the muon energy was varied from 20 GeV to 10 TeV. A muon event was considered showering if $\frac{\Delta E}{\Delta X} > 2.85$ MeV/cm where $\frac{\Delta E}{\Delta X}$ is the total muon energy loss divided by its path-length. For each muon event we applied Eqn. 1 to the observed photo-electrons of all PMTs in the Cherenkov cone and obtained the average of the corrected photo-electrons over 0.5 m along the muon track. This corrected dL/dX distribution of a normal ionizing muon and a showering muon can be found in Fig. 1.

For a normal ionizing muon the dL/dX distribution is approximately constant whereas for a showering muon the dE/dX histogram can show upward fluctuations as the muon undergoes Bremsstrahlung. To distinguish between these cases we construct a χ^2 defined as follows:

$$\chi^2 = \sum_{i=1}^{N-2} \left[\frac{(Q_{corr}^i - <Q_{corr}>)^2}{\sigma_{q_i}^2} \right] + \left(\frac{<Q_{corr}> -Q(l)}{\sigma_{<Q_{corr}>}} \right)^2 \tag{2}$$

where Q_{corr}^i is the corrected number of photo-electrons averaged over every 0.5 m along the muon track obtained using equation 1; $<Q_{corr}>$ is the mean of all Q_{corr}^i upto the last 1 m of the muon track; σ_{q_i} is the statistical error in $<Q_{corr}^i>$; and $\sigma_{<Q_{corr}>}$ is the statistical error in $<Q_{corr}>$. The second term in Eqn. 2 is used to increase the χ^2 value in case $<Q_{corr}>$ becomes much larger than $Q(l)$ which is the mean expected photo-electrons for a ionizing muon of path-length l. An event was considered showering if $[<Q_{corr}> -Q(l)] > 0$ and $\frac{\chi^2}{N-2} > 33$.
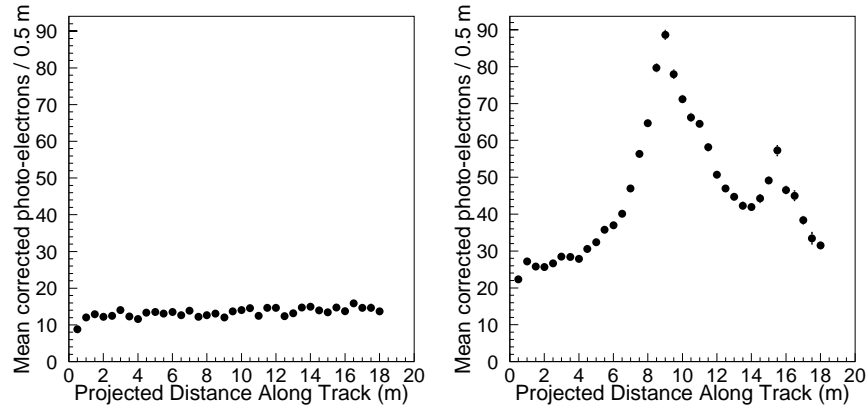
Fig. 1. The figure on the left shows the approximately flat dL/dX distribution of a normal ionizing muon of energy 20 GeV. The figure on the right shows the dL/dX distribution of a showering muon of energy 10 TeV and one can see the large upward fluctuations. Both muons have the same entry point and direction.

3. Energy spectrum of upward showering muons

We applied the above algorithm to an equivalent 40-year atmospheric neutrino Monte-carlo [5] to isolate the upward showering muons. The energy distribution of the resulting event sample is shown in Fig. 2. The mean energy of the parent neutrinos of the showering upward muons is peaked at ~ 1 TeV, whereas that for upward stopping muons is ~ 10 GeV and for non-showering through-going muons is ~ 100 GeV. The total flux of upward showering muons is about 10 times smaller than non-showering muons. The angular resolution for upward showering muons is estimated to be $\sim 1.4°$ from the Monte-Carlo.

4. Astrophysical Searches

With this algorithm we found a total of 294 upward showering muons among all the upward thru-muons in the Super-K-I data set . As an example of astrophysical point source search, we looked for a statistically significant excess of showering upward muons in a cone of half-angle 5° around the Earth, the Sun and the Galactic Center for possible signatures of WIMPs. Only high mass WIMPs can produce upward showering muons and most of this signal would be contained within 5° around the source [6]. As we can see from the first row of Table 1. no events are seen in this cone, thus ruling out the possibility of any WIMP-induced upward showering muons. The flux limits obtained from upward showering muons will be more stringent than the limits which have been obtained using the entire upward through-going muon data set in Ref [5].
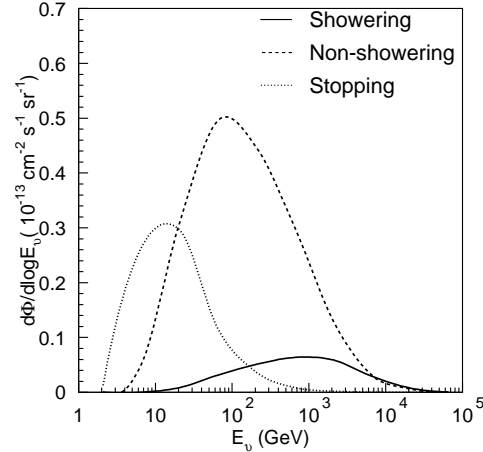
Fig. 2. Energy spectrum of all the 3 categories of upward muons as measured from the 40 year atmospheric neutrino Monte-carlo. The solid line indicates the sample of showering through-muons . The dashed line indicates the sample of thru-muons which lose energy only by ionization The dotted line shows the same for stopping muons

Data-set	Earth		Sun		Galactic Center	
	Data	Background	Data	Background	Data	Background
Showering upmus	0	0.3	0	0.5	0	0.6
All up-thrumus	2	1.9	2	3.5	3	5.0

Table 1. Table of observed and expected (from atmospheric neutrinos) upward showering muons (first row) and all upward through-going muons (second row) in a cone of half angle 5° around the Earth, Sun and Galactic Center.

5. References

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