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Upward Showering Muons in Super-Kamiokande

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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, e^+e^- pair production and photonuclear 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 as well as results from oscillation analysis.

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. The energy of the parent neutrinos of the upward stopping and upward thrugoing muons is peaked at around 10 GeV and 100 GeV respectively [1].

Below muon energy of about 1 TeV 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 [2]. In water, the critical energy of a muon (where radiative and ionization energy losses are equal) is $\sim$ 1 TeV [2]. 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. 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 a constant amount of Cherenkov light per unit track length. However, for a muon which undergoes radiative energy losses, the generated photons further produce an electromagnetic shower, 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 :

$$q_{corr}(\text{corr. pe}) = K\frac{Qd_w e^{\left(\frac{d_w}{L_{wt}}\right)}}{F(\theta)} \tag{1}$$

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(=1/2500). We then calculate the average charge in small track intervals (50 cm) along the muon track

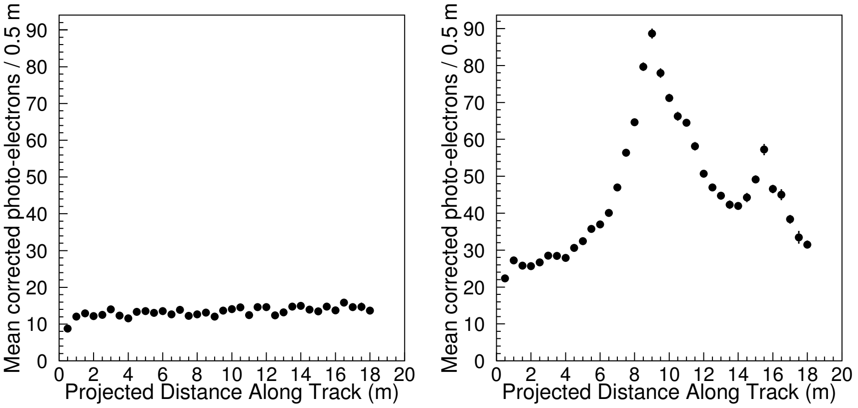

Figure 1. The figure on the left shows the approximately flat dL/dX distribution of a normal ionizing muon of energy 20 GeV. The figure on the right shows the dL/dX distribution of a showering muon of energy 10 TeV.

(Q^i_{corr}):

$$Q^i_{corr}(\text{corr. pe}) = \frac{\sum q_{corr}}{N_{pmt}} \tag{2}$$

We then compare Q^i_{corr} evaluated in each bin with the averaged corrected charge $< Q_{corr} >$ over all track-lengths:

$$< Q_{corr} >= \frac{\sum\limits_{i=4}^{N-3} \left(Q^i_{corr}/\sigma^2_{Q^i_{corr}}\right)}{\sum\limits_{i=4}^{N-3} 1/\sigma^2_{Q^i_{corr}}}. \tag{3}$$

For a normal ionizing muon this dL/dX (light deposited/tracklength) distribution is approximately constant whereas for a showering muon the dL/dX histogram can show upward fluctuations as the muon undergoes Bremsstrahlung. This is illustrated in Fig. 1, which shows the corrected dL/dX distribution of a normal ionizing muon and a showering muon with the same entry points and directions. To distinguish between these cases we construct the variables $\chi^2_{showering}$ and Δ as follows:

$$\chi^2_{showering} = \sum_{i=4}^{N-3} \left\{ \frac{[Q^i_{corr} - < Q_{corr} >]}{\sigma_{Q^i_{corr}}} \right\}^2, \tag{4}$$

where $< Q_{corr} >$ is defined in Eqn. 3, Q^i_{corr} is defined in Eqn. 2; $\sigma_{Q^i_{corr}}$ is the statistical error in Q^i_{corr}:

$$\Delta = [< Q_{corr} > -Q(l)], \tag{5}$$

where $Q(l)$ is the expected value of $< Q_{corr} >$ for an ionizing muon of track-length l. An event was identified as showering if it satisfies any one of the following constraints on $\chi^2_{showering}$/DOF or Δ : ($\chi^2_{showering}/DOF >$ 20 and $\Delta >$ 2.5 corr. pe) OR ($\chi^2_{showering}/DOF >$ 30 and $\Delta >$ 2.0 corr. pe) OR ($\chi^2_{showering}/DOF >$ 40 and $\Delta >$ 1.0 corr. pe) OR ($\chi^2_{showering}/DOF >$ 50 and $\Delta >$ 0.5 corr. pe) OR ($\Delta >$ 4.5 corr pe), where DOF is the number of degrees of freedom. With this cut the efficiency of detecting upward showering muons is $\simeq 71\%$ where the efficiency is obtained by estimating how many events detected by these cuts have total energy loss greater than 2.85 MeV/cm in the inner detector.

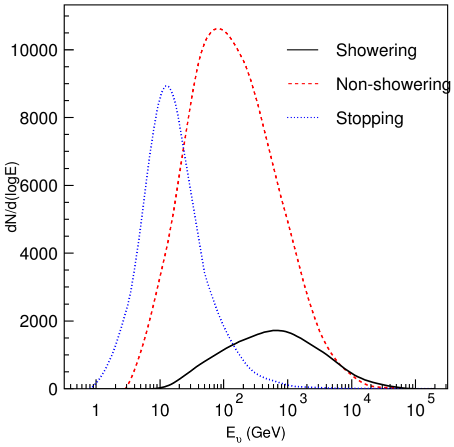

Figure 2. Energy spectrum of all the 3 categories of upward muons as measured from the 100 year atmospheric neutrino Monte-carlo.

3. Energy spectrum of upward showering muons

We applied the above algorithm to an equivalent 100-year atmospheric neutrino Monte-carlo as described in Ref. [1] 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 $\sim$ 1 TeV, whereas that for upward stopping muons is $\sim$ 10 GeV and for non-showering through-going muons is $\sim$ 100 GeV. The estimated angular resolution of this sample is about 1.4°. We found 309 upward showering muons (out of 1892 upward thrugoing muons) when applied to 1680 days upward-going muon sample. In this sample, the contamination from downward cosmic ray muons due to multiple coulomb scattering is estimated to be $8.63^{+12.3}_{-5}$ for $0 < cos(\theta) < -0.1$. This background is then subtracted from the upward showering muon data set.

4. Oscillation Analysis

The observed atmospheric neutrino dataset seen in Super-K is consistent with neutrino oscillations with $\Delta m^2 \simeq 0.0024\, eV^2$ and $\sin^2(2\theta) = 1.0$ [1, 3]. Given these values for the neutrino oscillation parameters, the oscillation probability is negligible for showering muons, since their parent neutrinos have a mean energy of $\simeq$ 1 TeV. The chi-square function used for comparison of data and Monte Carlo is same as that used for oscillation analysis with all neutrino datasets [1]. Using only the showering muon dataset the minimum χ^2 value = 4.68 for 7 DOF, which is located at $(\sin^2(2\theta) = 0.91,\ \Delta m^2 = 1.04 \times 10^{-2}\ eV^2)$. For null oscillation $(\sin^2(2\theta) = 0)$, we found a χ^2 value of 6.52 for 9 DOF, where only the overall normalization is the free parameter. Since the minimum χ^2 is not significantly different than the χ^2 obtained for null oscillation, we do not ascribe any importance to the chi-square minimum. For all upward through-going muons, the χ^2 value for null oscillation is 19.56 for 9 DOF. The best fit χ^2 value for only upward thrugoing muons is 7.62 for 7 DOF corresponding to $\Delta m^2 = 0.0024\, eV^2$ and $\sin^2(2\theta) = 0.96$. The zenith angle distribution of upward showering muons as well as all thrugoing muons, along with the expected distribution (with null oscillations), as well as with the best fit solution is shown in Fig. 3. Figure 4 shows the $\chi^2 - \chi^2_{min}$ distributions projected to $\sin^2 2\theta$ and Δm^2

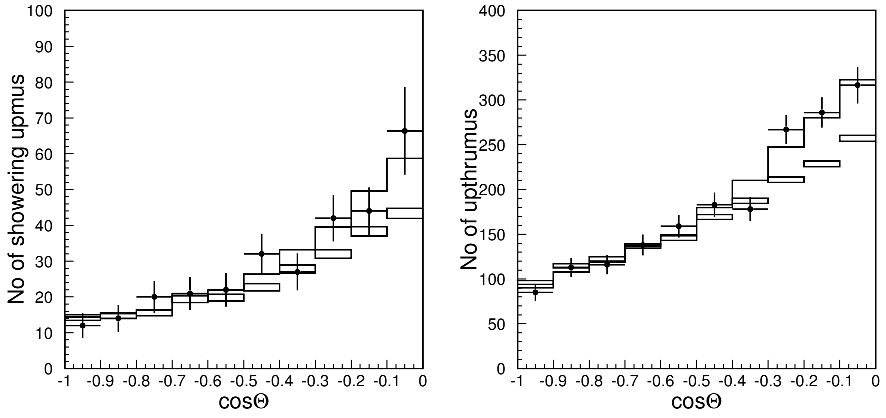

Figure 3. Zenith angle distribution of upward showering muons (left) and all upward thrugoing muons (right). The dots represent the data points with statistical error bars. The solid line shows the best fit at the minimum χ^2 value and after scaling with the best fit estimates of the systematic parameters. The solid box show the expectation at null oscillations and normalized by livetime.

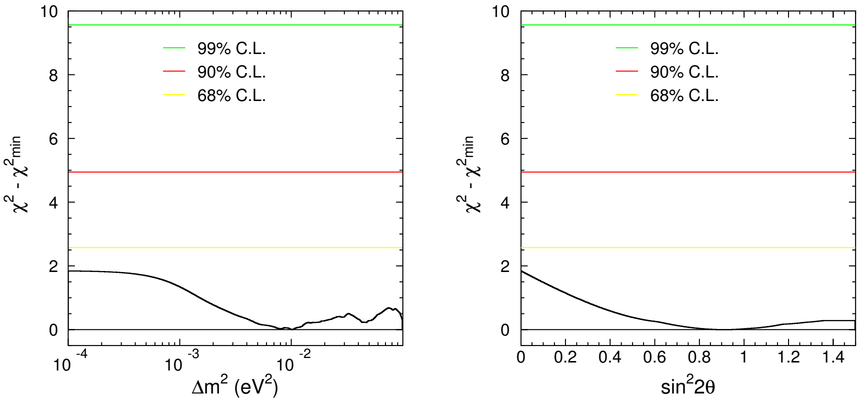

Figure 4. $\chi^2 - \chi^2_{min}$ projected onto the $\sin^2 2\theta$ and Δm^2 axes. The minimum value at each $\sin^2 2\theta$ and Δm^2 is plotted.

axes, in which the minimum $\chi^2 - \chi^2_{min}$ values for each $\sin^2 2\theta$ and Δm^2 are plotted. As we can see , null oscillation is allowed even at 68 % confidence level for upward showering muons. This shows that the highest energy muon neutrino dataset (with mean parent neutrino energy $\simeq$ 1 TeV, path-lengths of order 10,000 km and $\Delta m^2 \simeq 0.0024\, eV^2$) is consistent with null oscillation.

References

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