Muon energy determination with the Baikal neutrino telescope NT-96

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Abstract

We present an algorithm to determine the energy of muons crossing the Baikal neutrino telescope NT-96. The obtained error in the logarithm of the energy is 0.4-0.5, depending on the muon energy. We compare experimental and Monte Carlo energy spectra of atmospheric muons and atmospheric neutrinos.

1 Introduction

The primary challenge for deep underwater detectors is the identification of upward moving muons generated in neutrino interactions. The concentration on the lower hemisphere is given by the flux of downward muons caused by the interaction of the cosmic rays with the atmosphere. This flux exceeds the flux of upward moving muons from atmospheric neutrino interactions by a factor of 10^6 at a depth of $\sim 1\,000$ mwe. As it has been shown in [1] already for the relatively small array NT-96 the separation of neutrino events can be achieved, using the directional information of the muon only. For doing neutrino astronomy it becomes important not only to use the directional information of the muon, but also to get a handle on the muon energy. This is because the energy spectrum of the atmospheric neutrinos is following a power law $E^{-\gamma}$ with $\gamma \sim 2.7$ [3] up to an energy of $\sim$100 GeV and steepen towards $\gamma \sim 3.7$ at higher energy, while the neutrinos from a cosmic accelerator (assuming first order Fermi mechanism for acceleration) are assumed to have a harder spectra with $\gamma \sim 2$ [3]. This results in a negligible background from atmospheric neutrinos for neutrino energies above a certain (flux dependent) threshold. The knowledge about the order of magnitude of the energy of a neutrino event enables thus discriminating against atmospheric background. In this paper it will be shown that with a straight-forward parameterization of the light output for muons of different energy and using the calculated probability of a measured amplitude for a muon fixed in space, a likelihood reconstruction yields an energy resolution of 0.4–0.5 orders of magnitude. This method was applied to the neutrino events found in [1]. The determined energy was found to be in agreement with what one expects from atmospheric neutrinos. The determination of the muon energy will enhance the capability of the present neutrino detectors in identifying cosmic neutrino events.

The detector NT-96 installed 1996 at Lake Baikal was the world first neutrino telescope which has been able to separate atmospheric neutrinos events from atmospheric muon events. The detector consists of 96 photomultipliers (48 channels) mounted on four strings. Each string has a length of 70 m and a distance of about 18 m to the others. The array, now upgraded to 192 photomultipliers, is installed at a depth of 1100 meters.

2 Reconstruction Method

The reconstruction consists of two steps: firstly, the space coordinates are reconstructed with a conventional maximum likelihood method. It uses the time and amplitude information on each hit OM, and the probability not to be hit on each non-hit OM. This reconstruction is done based on a model of a minimal ionizing muon [5].

Secondly, the energy is estimated by computing the likelihood of the weighted average of the muon energy. This is done with the formula

$$E_{\text{rec}} = \int_{E_{\min}}^{E_{\max}} E \cdot P(E)dE$$

[1] for a full author list, see talk of HE.4.2.04 L.Kuzmichev

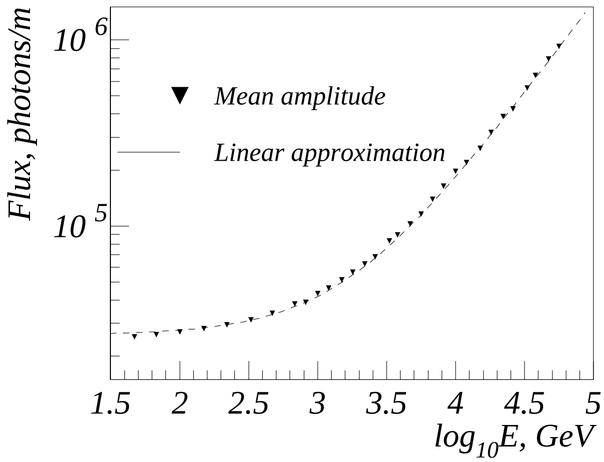

Figure 1: Average light emission as a function of the muon energy.

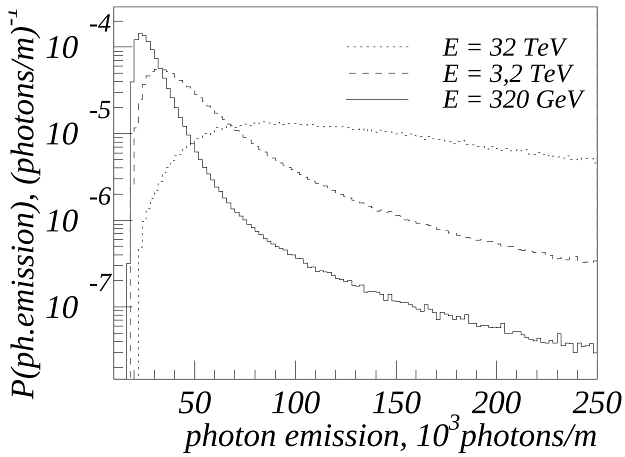

Figure 2: Distribution of the emission frequency for a certain light intensity for muons with different energies.

During this step, the track coordinates are kept fixed. The estimation of the amplitude likelihood uses the following models for different effects:

1. A table of the probability to get a certain amplitude response for a certain muon energy and light attenuation. This table was created by the Monte Carlo program DADA which is based on GEANT-3.21 [7]. The average number of emitted photons is shown in figure 1, together with the linear approximation

$$\overline{N_{\text{ph}}}(E) = \overline{N_{\text{ph}}}(\text{naked muon}) \cdot (1.2 + 0.8 \cdot E/\text{TeV})$$

   Figure 2 shows the photon emission distribution for muons with different energies. Although these distributions depend on the detection area, they are independent on the distance to the photomultipliers.

2. The absorption in the water. Here, a parameterization of the wavelength dependent water attenuation length published in [6] is used.

3. The wavelength dependent quantum efficiency of the optical module, including the pressure housing. This parameterization is based on [8].

4. The behavior of the detector. This includes:

   - The number of photo electrons for a certain photon flux is Poisson distributed.
   - The Quasar photomultiplier [8] has a typical amplitude (1 p.e.) resolution of 70%.
   - The photomultipliers are paired in coincidence, forming one channel.
   - Each channel has a 400 Hz noise from accidental coincidences of dark noise and bioluminescence.
   - The maximal hit probability of a channel is 95–97.5% even at high illuminations.

For a hit channel, the probability to measure a certain amplitude A is

$$P(A) = \int_0^\infty P(\Phi_{\text{OM}}) \frac{\Phi_{\text{OM}}^A e^{-\Phi_{\text{OM}}}}{\Gamma(A+1)} \cdot \left(1 - e^{-\Phi_{\text{OM}}}\right) d\Phi_{\text{OM}}$$

and the probability for a channel not to be hit

$$P_{\rm nohit,2} = 1 - \int_0^\infty P(\Phi_{\rm OM}) \cdot \left(1 - e^{-\Phi_{\rm OM}}\right)^2 d\Phi_{\rm OM}$$

with $P(\Phi_{\rm OM})$ being the energy dependent probability to get a certain photon flux $\Phi_{\rm OM}$.

Energy reconstruction is only applied to tracks fulfilling the standard quality criteria for track reconstruction described in [5]. A test with isotropic simulated muons in the range 80 GeV to 100 TeV is shown in figure 3. The reconstructed energy parameter α (which is $\log_{10} E_{\rm rec}$ of the reconstructed energy $E_{\rm rec}$ in GeV[2]) is limited to $2.0 \ldots 5.0$ by the range of the muon energy tables used in the reconstruction. Above 1 TeV, the energy resolution is about 0.45 orders of magnitude. Stronger cuts do not improve the energy resolution. For bigger detectors (NT-200 and up) it is expected that the energy resolution will improve. For higher energies, this reconstruction method needs to be adjusted for correlations between the amplitude measurements of the different detector channels which are neglected at the present stage.

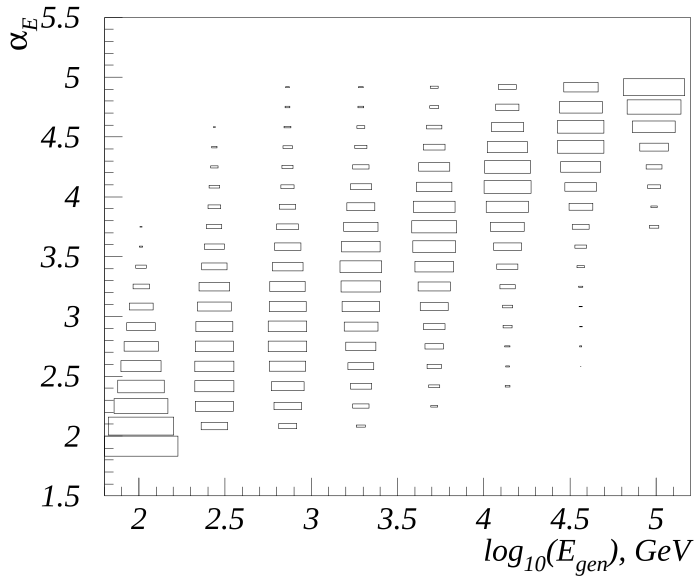

Figure 3: Reconstructed energy parameter α, as a function of the generated muon energy.

We also tested the stability of the reconstruction method with respect to variations of several parameters of the detector, such as water attenuation, quantum efficiency of the photomultiplier etc. It turned out that the energy reconstruction is stable with respect to reasonable changes of these parameters.

3 First Results

As a first test, the method was applied on atmospheric muons. Figure 4 shows the reconstructed Monte Carlo muon spectrum, compared to reconstructed experimental data. Due to the relatively broad energy resolution, the reconstructed energy parameter spectrum differs significantly from the true triggered energy spectrum. To reproduce the triggered energy spectrum, an unfolding operation is necessary.

The method described above was applied to the neutrino events found within 70 days of NT-96 lifetime[1] as well as to a sample of atmospheric neutrino Monte Carlo events. The distribution of the reconstructed energy parameter α of the Monte Carlo neutrinos is shown in figure 5. The reconstructed energies of the NT-96 neutrino events are marked and are compatible with the spectrum of atmospheric neutrinos.

The cuts applied to these events are optimized for a separation of atmospheric neutrino events from the background of atmospheric muons which makes the reconstructed energy parameter spectrum different from the downgoing muon spectrum in figure 4. Particularly, cuts on a minimal number of channels $N_{\rm ch} \geq 9$ and a minimal detected track length $Z_{\rm len} > 35$m shift the energy parameter to higher values than for all triggered upward events.

4 Conclusions and Outlook

The results obtained with the described reconstruction method show the possibility to estimate the energy of muons detected by the Baikal Neutrino Telescope. The reconstruction works well in an energy range between

[2]Because of the steep falling muon spectrum, the reconstructed energy does not give the best estimate of the muon energy. For this reason, the term ‘energy parameter’ is used instead.

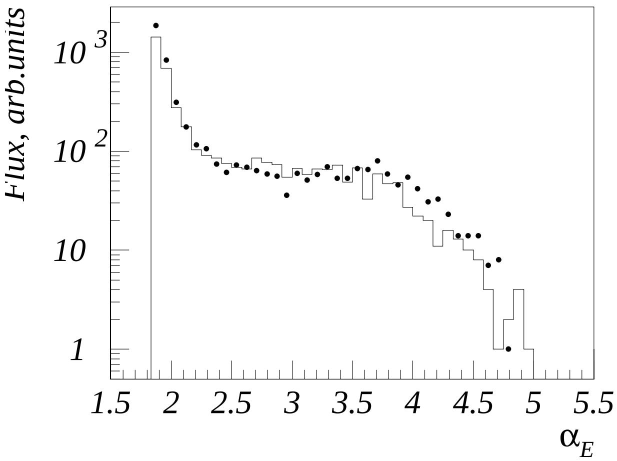

Figure 4: Reconstructed energy parameter of atmospheric muon. Points: experimental data. Solid line: MC results.

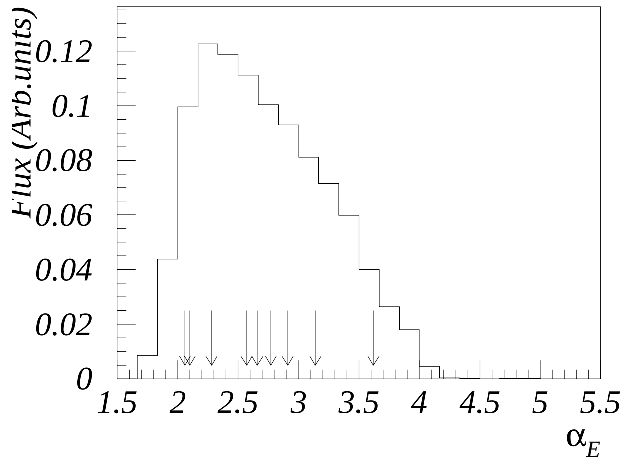

Figure 5: Reconstructed energy parameter of atmospheric neutrinos. Arrows indicate the reconstructed energy parameter of the observed neutrino events from [1].

1 TeV and 30 TeV. For a further determination of flux limits, an unfolding procedure will be applied to the data.

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