Muon induced electromagnetic shower reconstruction in ANTARES neutrino telescope

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Abstract: The primary goal of the ANTARES telescope is the detection of high energy cosmic muon neutrinos. The neutrinos are identified by the upward going muons that are produced in charged current neutrino interactions in the vicinity of the detector. The Cherenkov light produced by the muons in the detection volume is measured accurately by an array of photosensors. Muons that are going downward are background for neutrino searches. These muons are the decay products of cosmic-ray collisions in the Earth’s atmosphere. The energy loss in water of a muon with an energy above a TeV is characterized by discrete bursts of Cherenkov light originating mostly from pair production and bremsstrahlung (electromagnetic showers). This paper presents a method to identify and count electromagnetic showers produced by the muons. The method can be used to select a sample of highest energy muons with the ANTARES detector.

Keywords: Neutrino telescope, Electromagnetic shower reconstruction, High energy muons.

1 Introduction

The ANTARES neutrino telescope is located on the bottom of the Mediterranean Sea, roughly 40 km off the French coast. The main objective is the observation of extraterrestrial neutrinos. Relativistic charged leptons produced by neutrino interactions in and around the detector produce Cherenkov light in the sea water. This light is detected by an array of photomultiplier tubes (PMTs), allowing the muon direction to be reconstructed. The muon energy loss can be estimated from the sum of the measured number of photoelectrons.

The detector is installed at a depth of 2475 m and consists of twelve vertical lines approximately 450 m long equipped with a total of 885 PMTs. The lines are separated from each other by about 65 m, anchored to the sea bed by a dead weight and held taut by a buoy located at the top. The instrumented part of the line starts 100 m above the sea bed, with 25 storeys every 14.5 m along the line. A storey consists of three PMTs pointing downward at an angle of 45° with respect to the vertical direction, in order to maximise the detection efficiency of upward going tracks.

ANTARES is operated in the so called all-data-to-shore mode: all pulses above a threshold (typically 0.3 photoelectrons) are digitized off-shore and sent to shore to be processed in a computer farm. This computer farm applies a set of trigger criteria in order to separate muon-induced Cherenkov light from background light. The main sources of the background light are the decay of $^{40}$K nuclei and the bioluminescence of organisms in the sea water. A detailed description of the ANTARES detector is given in [1].

Although ANTARES is optimised for upward going particle detection, the most abundant signal is due to the atmospheric downward going muons produced by the interaction of primary cosmic-rays in the atmosphere. Being the most penetrating particles in such air showers, muons with enough energy can reach the detector and are reconstructed by the detection of the Cherenkov light they emit when propagating through water. The ANTARES detector has the capability to follow highly energetic muons over a few hundred metres.

The processes contributing to the energy loss of a muon in water include ionisation, $e^+e^-$ pair production, bremsstrahlung, and photonuclear interactions. Below 1 TeV, the muon energy loss is dominated by the continuous ionisation process. Above 1 TeV, the muon energy loss is dominated by pair production and bremsstrahlung [2], which are radiative processes classified as electromagnetic showers. They are characterized by large energy fluctuations and discrete bursts along the muon track. The average muon energy loss per unit track length due to these electromagnetic showers increases linearly with the energy of the muon allowing its energy to be determined. Counting electromagnetic showers along muon tracks gives an estimate of the muon energy [3] and can help in designing a better energy reconstruction algorithm. A similar measurement technique as the one presented in this article has been published recently by the Super-Kamiokande experiment [4].
The primary composition of the flux is subdivided into only five mass groups, namely proton, helium, nitrogen, magnesium and iron.

2 Algorithm for shower identification

The purpose of the electromagnetic shower identification is to distinguish Cherenkov photons emitted continuously along the muon track, from the Cherenkov photons induced by electromagnetic showers. Because of the radiation length in water ($\lambda_{\text{w}} = 35$ cm), these showers never extend more than a few metres and can be considered point-like light sources in the ANTARES detector. The showers can be identified from a localised increase of the number of emitted photons above the continuous baseline of Cherenkov photons emitted by a minimum ionizing muon.

In what follows, a hit is a photomultiplier signal exceeding a threshold of 0.3 photoelectrons. The shower algorithm consists of two steps. The first step is to identify and reconstruct downward going muon track candidates. In the second step, a distinct shower candidate is identified by looking for an accumulation of hits on a point along the muon path. The criteria to isolate the accumulation are defined from a simulation code based on Corsika [5].

2.1 Simulation

Cosmic-ray interactions in the atmosphere including shower development were simulated for primary energies between 1 TeV and $10^5$ TeV, and incident angles between zero (vertical) and 85 degrees with Corsika. The primary cosmic-ray composition and flux model considered was a simplified version[ of the Hörandel model [6]. The hadronic interaction model chosen was QGSJET [7]. The result of the Corsika simulation consists of muons with their positions and times and kinematic vectors on the surface of the sea. The muon propagation through water, the discrete energy losses at high energies, the Cherenkov light production and propagation, including scattering, and the response of the detector was simulated using the ANTARES KM3 code [8]. KM3 uses tables generated from a simulation with GEANT 3 which parametrise the arrival time and the amount of light detected by individual PMTs. These tables take into account the angular dependence of the acceptance of the PMT as well as the measured properties of the water at the ANTARES site. The muon propagation uses the MUSIC code [9] and is done in short steps (1 m). If the energy loss of the muon over the step exceeds a threshold (1 GeV), an electromagnetic shower is initiated and shower photons are emitted, otherwise if the energy loss of the muon over the step is below the threshold muon Cherenkov photons are emitted. The optical background was assumed flat at a rate of 60 kHz on each photomultiplier.

2.2 Algorithm

Muon events are reconstructed by using an existing algorithm [10, 11] which provides an estimate of the direction and position of the muon at a given time. Measured hit times are compared to the expected arrival time of direct Cherenkov photons. The expected Cherenkov photon arrival time $t_i^{CK}$ for each hit $i$ is calculated as (see Figure 1):

$$t_i^{CK} = t + \frac{1}{c} \left( z_i - z - \frac{r_i}{\tan \theta_{CK}} \right) + \frac{n}{c} \frac{r_i}{\sin \theta_{CK}} ,$$

where $t$ is the time where the muon passes point $(r, z)$, $c$ is the speed of light in vacuum, $n$ is the refraction index of water ($n$ is about 1.38), $\theta_{CK}$ is the Cherenkov angle for a relativistic muon in water ($\theta_{CK} = 42^\circ$) and $r_i$ is the perpendicular distance between the muon trajectory and the PMT. Equation (1) separates the direction along the track and the direction perpendicular to the track. The direction along the track (z-coordinate) is given by the muon momentum vector. The direction perpendicular to the track (r-coordinate) is given by the photon momentum vector in water. Hits too far in time from the expected muon hit time $t_{\text{min}} < t_i - t_i^{CK} < t_{\text{max}}$ are assumed to be background hits and are rejected, whereas direct hits have a roughly Gaussian distribution at zero with a width of 20 ns. The value for $t_{\text{min}} = 20$ ns is given by mainly the dispersion of light in water and the timing resolution of the PMT, whereas $t_{\text{max}} = 200$ ns is defined by the value where the number of signal hits approaches the level of background hits. Furthermore, the above defined time interval is subdivided into two intervals. The early interval contains mostly muon Cherenkov photons and is given by $|t_i - t_i^{CK}| < t_{\text{min}}$. The Cherenkov photon emission position ($\zeta_i^{CK}$) along the muon trajectory is given by:

$$\zeta_{\text{CK}} = z_i - \frac{r_i}{\tan \theta_{CK}} .$$

The late interval is defined by $t_{\text{min}} < t_i - t_i^{CK} < t_{\text{max}}$ and contains mostly electromagnetic shower photons. These shower photons may not necessarily be emitted at the Cherenkov angle from the muon track. The emission angle is left as a free parameter and, with the photon emission
taking place at $\zeta_i$ (see Figure 1), the hit time is given by

$$t_i = t + \frac{\zeta_i - z}{c} + \frac{n}{c} \sqrt{r_i^2 + (z_i - \zeta_i)^2}. \tag{3}$$

Equation (3) can be solved for $\zeta_i^\pm$, yielding:

$$\zeta_i^\pm = -B_i \pm \frac{B_i^2 - 4AC_i}{2A},$$

where

$$A = 1 - n^2,$$

$$B_i = 2(n^2z_i - z - c(t_i - t)),$$

$$C_i = c^2(t_i - t)^2 + 2cz(t_i - t) + z^2 - n^2(r_i^2 + z_i^2).$$

All calculated $\zeta_{iC}^\pm$, $\zeta_i^+$ and $\zeta_i^-$ positions along the muon track are collected in a one-dimensional histogram. As an example of such a histogram, Figure 2 shows all the calculated photon emission positions along the muon trajectory. The electromagnetic showers are identified by an excess of photons above the continuous baseline of photons emitted by a minimum ionizing muon. Two excesses are visible that can be attributed to the two reconstructed showers.

### 3 Selection and results

The selection and performance of the shower identification algorithm has been studied and validated with a sample of simulated atmospheric multi-muons with constant background light as described in section 2.1.

#### 3.1 Selection

The shower algorithm makes use of tracks fitted with the muon reconstruction algorithm described in [10] with two additional criteria. These criteria require the tracks to be traced for at least 125 m and to have a minimum of twelve hits used in the track reconstruction. These selected tracks account for around 65% of all reconstructed tracks. The advantage of the selected tracks is not only that the direction of the tracks is better reconstructed, but also that the tracks are long enough to have a high probability to emit showers.

The parameters in the shower reconstruction algorithm are the width and the height of the peak. The analysis has been tuned to select showers with a high level of purity, possibly at the expense of efficiency. For each selected peak, the number of hits is integrated in a $\pm 5$ m interval around the peak center. Only peaks having at least 10 hits over the muon-track Cherenkov photon baseline in this interval of 10 m are selected. The number of baseline hits is defined as the average density of hits along the track times the interval width of 10 m. In addition, in order to suppress fake identified showers, hits from at least five different storeys are required in each peak.

#### 3.2 Results

The main result of the shower reconstruction algorithm is the shower multiplicity per atmospheric muon event. The atmospheric muon events are usually muons in a bundle with an average multiplicity of around 3.3. Figure 3 shows the event rate as a function of the number of generated showers with shower photons detected on at least five different storeys. Also shown is the number of reconstructed showers selected with the cuts mentioned in section 3.1. The average shower reconstruction efficiency over all shower energies is around 4%. The reconstruction algorithm starts to be efficient for shower energies above 300 GeV.

Figure 4 shows the number of generated showers with shower photons detected on at least five different storeys per atmospheric muon event as a function of the muon energy. The muon energy refers to the muon with the largest energy in the bundle. The number of generated shower and reconstructed shower increases as a function of the muon energy.
4 Conclusion

A method to identify showers emitted by atmospheric muons has been applied to simulated data of the ANTARES detector. The main differences between the shower light and the muon Cherenkov light are that the shower light is produced on a point along the muon path. The essential element of the algorithm is that the selection of shower photons is reduced to a one-dimensional problem. The performance of the identification algorithm has been validated using a sample of simulated atmospheric muon events.

The aim of this proceeding has been more to demonstrate the capability to detect electromagnetic showers than to make precise measurements. A more elaborated analysis is needed, in order to use the number of electromagnetic showers as a robust estimate of the muon energy. Moreover, the method discussed here for selecting showers emitted by downward going muons could be used also for upward going muons with the main purpose of selecting the highest energy upward going muons.

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