Energy reconstruction in neutrino telescopes

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Abstract: The energy is one of the most important parameters to discriminate between atmospheric and astrophysical events recorded by neutrino telescopes like ANTARES and IceCube. Here we introduce and describe a method to reconstruct the energy deposited by muons along their track, $\mathrm{d}E/\mathrm{d}X$, while crossing the fiducial volume of such a detector. Exploiting the close correlation between the energy deposit and the energy of charged particles above a few hundred GeV we use the reconstructed $\mathrm{d}E/\mathrm{d}X$ to derive the energies of the incident muon and the primary neutrino. We describe the basic ideas behind the algorithm and, applied to the ANTARES neutrino telescope, quantify its performance and discuss systematic uncertainties using both data and detailed Monte Carlo simulations.

Keywords: neutrino telescopes, energy reconstruction

1 Introduction

The detection of astrophysical neutrinos and the identification of their sources is one of the main aims of large neutrino telescopes operating at the South Pole (IceCube), in Lake Baikal and in the Mediterranean Sea (ANTARES). The vast majority of the neutrino candidates recorded by these experiments are of atmospheric origin. To discriminate and select events of potential astrophysical origin, the energy of the events is the prime parameter. It is expected that the astrophysical neutrino flux follows a harder spectrum (typically described by an E^{-2} energy dependence), whereas the atmospheric flux is falling more rapidly with increasing energy ($E^{-3.7}$ in the energy range typically accessible with current neutrino telescopes [2]).

Here we introduce and describe an algorithm to reconstruct the energy of both the muon traversing the detector and the primary neutrino. The algorithm has been developed within the ANTARES collaboration [1] and its use in several analyses lead to significant increase of their sensitivities [3, 4]. The underlying principles are nevertheless valid for all neutrino telescopes and similiar algorithms are being developed for example within the IceCube Collaboration [5].

The different neutrino interaction modes lead to different experimental signatures in neutrino telescopes. The signature of neutral current interactions are particle showers, i.e. very localized energy deposits and light emission. The rate of these events is limited by the available instrumented volume which acts as interaction volume. On the other hand their energy reconstruction is possible with rather good precision as they are usually fully contained. Muons emerging from charged current interactions of muon neutrinos provide the bulk of the neutrino induced data of ANTARES and other neutrino telescopes due to the extension of the fiducial volume beyond the instrumented volume. Whereas the direction of the muon track can be reconstructed with good precision, the reconstruction of its energy however is, due to the intrinsic fluctuations of the energy deposited within the detector volume, less obvious and the subject of this paper.

The fundamental idea behind the presented algorithm is to exploit the correlation between the energy of a charged particle in a medium and its energy loss. The latter is deposited along the muon track and can be denoted as energy deposit $\mathrm{d}E$ per tracklength $\mathrm{d}X$. At energies above the critical energy of a few hundred GeV, energy losses due to Bremsstrahlung become more important with respect to ionisation losses and a clear correlation between $\mathrm{d}E/\mathrm{d}X$ and the particle energy can be expected. If a significant amount of this energy deposit happens within or close to the instrumented volume of a neutrino telescope it can be detected via the recording of the emitted light along the muon track. One will then be able to reconstruct a measure of the (local) energy loss by dividing the measured amount of energy deposit by the reconstructed length of the track within the fiducial volume. Detailed Monte Carlo simulations are then used to exploit the discussed correlations to estimate the energy of the muon and the incident neutrino.

2 The $\mathrm{d}E/\mathrm{d}X$ energy estimator

2.1 $\mathrm{d}E/\mathrm{d}X$ estimation

We approximate the total muon energy deposit $\mathrm{d}E/\mathrm{d}X$ by an estimator ρ which can be derived on an event-by-event basis from quantities measured by the ANTARES detector:

$$\mathrm{d}E/\mathrm{d}X \approx \rho = \frac{\sum^{\mathrm{nHits}} Q_i}{\varepsilon(\vec{x})} \cdot \frac{1}{L_\mu(\vec{x})} \quad (1)$$

$\varepsilon(\vec{x})$ is the light detection efficiency and will be described in detailed below. Q_i denotes the charge recorded by a given photomultiplier tube i of the ANTARES detector. To suppress the influence of background light, we only consider the hits that remain after a hit selection based on the causality criterion assuming a Cherenkov light cone and that have been selected for the final step of the track reconstruction. The track length L_μ is taken as the length of the reconstructed muon path within a sensitive volume. This volume has been defined as the cylinder of the ANTARES instrumented volume extended by twice the approximate light attenuation length ($L_{\mathrm{att}} = 55\ m$) to take into account

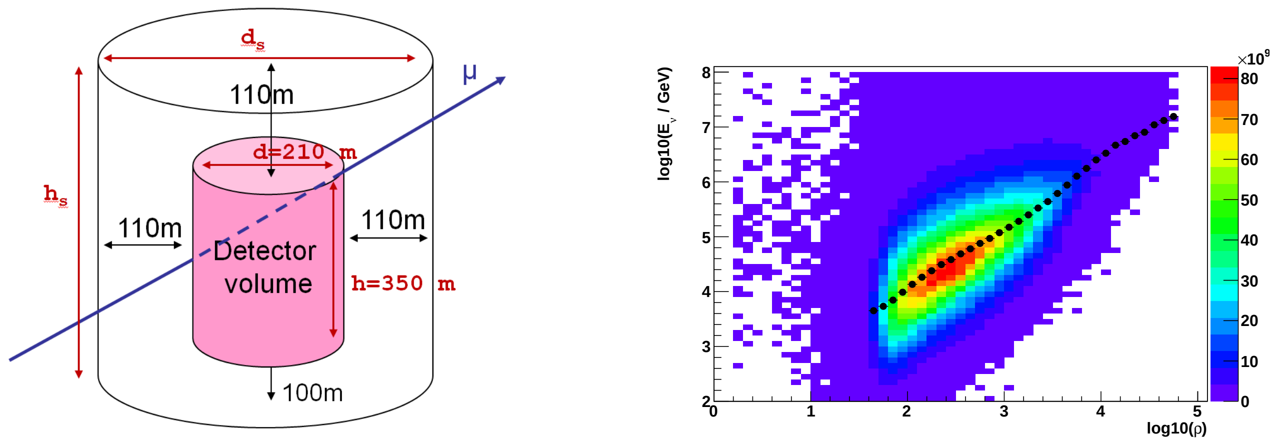


Figure 1: Left plot: Definition of the fiducial volume used to calculate the length of the muon track L_μ. The total size of the volume is given by $d_s = 430$ m and $h_s = 560$ m. Right plot: The correlation between the reconstructed $\mathrm{d}E/\mathrm{d}X$ and the true energy is used to calibrate the energy estimator. The black markers denotes the derived calibration table, i.e. the average true energy per $\mathrm{d}E/\mathrm{d}X$ bin.

the possibility of light entering the instrumented volume from the outside. It is depicted in Fig. 1, left plot.

The ANTARES light detection efficiency is depending on the geometrical position and direction of the muon track $\vec{x}$. This efficiency ε can be derived on an event-by-event basis as:

$$\varepsilon(\vec{x}) = \sum^{\mathrm{nOMs}} \exp\left(-\frac{r_i}{L_{\mathrm{abs}}}\right) \cdot \frac{\alpha_i(\theta_i)}{r_i} \qquad (2)$$

Here, the sum runs over all optical modules (OMs) that were active at the time the event was recorded. Modules become inactive for short periods of time, due to localized bioluminescence bursts which cause the data acquisition for modules close by to be stopped, or permanently, due to mechanical or electronical failures. The distance to the muon track r and the angle of incidence θ of the Cherenkov light is calculated for all nOM active modules. The latter is used to derive the angular acceptance $\alpha(\theta)$ of the optical modules. r is used to correct for light absorption in the water, with L_{abs} being the light absorption length. Finally a factor $1/r$ is applied to take into account the light distribution within the Cherenkov cone.

2.2 Energy estimation

Charged current muon neutrino simulations in combination with a time dependent detector simulation reproducing the actual data taking conditions of the ANTARES detector have been used to correlate the $\mathrm{d}E/\mathrm{d}X$ values calculated following Eq. 1 with the true energy of the incident neutrino or of the muon passing through the detector. These correlations are shown in the right plot of Fig. 1. Averaging the result in small $\mathrm{d}E/\mathrm{d}X$ bins ($\Delta(\log(\mathrm{d}E/\mathrm{d}X) = 0.1$), the distributions have been condensed into the final calibration tables. Given a $\mathrm{d}E/\mathrm{d}X$ value, these tables can be used easily to derive the corresponding estimated energy. Linear interpolations in log-log scale are used between the discrete bins of the tables. As baseline, this calibration step is performed using neutrino simulations fulfilling the quality cuts described in [7]. It should be noted that, depending on the intended application of the energy estimator, a dedicated calibration might become necessary (e.g. energy reconstruction of atmospheric muons, etc.).

3 Data vs. Monte Carlo comparison

To make sure that the energy estimation will be as reliable for real data as it is for simulated events (see Sec. 4 below), a detailed data vs. Monte Carlo comparison has been performed. This comparison has been conducted at several levels, ranging from the input parameters that are used for the energy estimation as given in Eq. 1 and 2 to the distribution of the final reconstructed energies and for the main event signatures available with sufficient statistics: atmospheric muons and muon neutrinos. Several event selection criteria have been tested and all distributions show a very satisfactory agreement between data and simulations. Examples are shown in Fig. 2. It can therefore be expected to obtain results similar to those for Monte Carlo simulations when the estimator is applied to real data. As final example, the distribution of the ρ estimator (see Eq. 1) is shown in the left plot of Fig. 3 for events fulfilling the high quality event selection criteria used for the determination of the atmospheric neutrino spectrum [3]. It should be noted that the total number of events selected from data is commonly about 25 % higher with respect to the expectations from flux parametrizations (see for example [4, 6]). Here we are only interested in the agreement of the shape, the distributions have therefore been normalized to unity.

4 Performance

4.1 Event selection

After the verification of agreement between data and Monte Carlo, the performance of the energy estimator can be derived from Monte Carlo simulations. The described method has therefore been applied to charge current neutrino simulations reproducing the ANTARES data taken in the period 01/2008-12/2011. As an example, the event selection criteria follow the ones developed during the search for point like sources [7]. They contain a cut on the reconstructed zenith angle $\theta > 90^\circ$, a requirement on the reconstruction quality parameter $\Lambda > -5.2$ as well as a cut on the estimated angular uncertainty of the track reconstruction $\beta < 1^\circ$.

To improve the energy reconstruction quality, two addi-

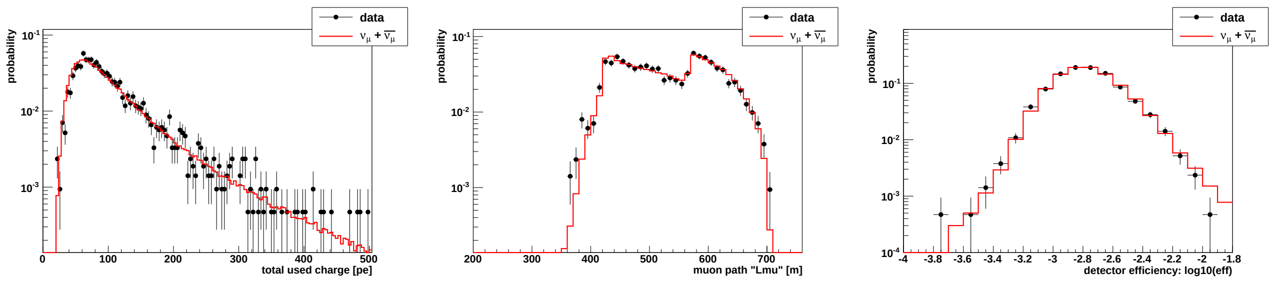


Figure 2: Comparison between data (black markers) and Monte Carlo (red histogram) for events selected for the determination of the atmospheric neutrino spectrum [3] for the main input variables to the energy estimator (cf. Eq. 1). Left plot: The total charge of all used hits $\sum^{\mathrm{nHits}} Q_i$. Middle plot: The tracklength within the fiducial volume $L_\mu(\vec{x})$. Right plot: The detection efficiency $\varepsilon(\vec{x})$.

tional criteria based on internal parameters of the energy estimator have been developed:

- $\log(\rho) > 1.6$
- $L_\mu > 380$ m

Events with path lengths within the fiducial volume L_μ shorter than 380 m are dominated by events passing outside the instrumented volume which leads to an overestimation of the energy. The cut at the limit of the $\rho - E_{\mathrm{MC}}$ table ($\log(\rho) > 1.6$) is necessary to define the validity of the energy estimator: the correlation between energy and energy deposit practically disappears at low energies and, in addition, the current version of the calibration table is only valid above $\log(\rho) > 1.6$ (see Fig. 1).

4.2 Efficiency

The efficiency of the algorithm has been estimated with the help of the above mentioned Monte Carlo simulations. An efficiency of 1 is found over a wide range of energies for events fulfilling the reconstruction quality cuts. The two additional selection criteria related to the energy estimator naturally degrade the efficiency. Whereas the cut on $\log(\rho)$ simply reflects the validity range of the estimator, the minimal track length requirement of $L_\mu > 380\ m$ removes high energy tracks that pass outside the instrumented volume. Nevertheless this criterion is necessary to avoid a bias introduced by these external events and starts to degrade the efficiency of the algorithm for events above roughly 100 TeV, therefore affecting only a marginal amount of ANTARES data.

4.3 Resolution

Applying all selection criteria and weighting the neutrino simulations to follow an astrophysical E^{-2} energy spectrum, the performance of the energy estimator has been derived. As can be seen in Fig. 3, an average resolution of $\log(E) \approx 0.45$ ($\log(E) \approx 0.7$) has been achieved for the reconstruction of the muon (neutrino) energy.

The main limitation to the energy resolution is the limited size of the detector, which, combined with the statistical nature of the energy loss processes, leads to an insufficient sampling of the energy losses along the muon track. The reconstruction of the neutrino energy suffers in addition from the fluctuations induced in the charged current interaction. Minor additional contributions are related to the uncertainties of the directional reconstruction and the selection of the hits used as input for the energy estimation.

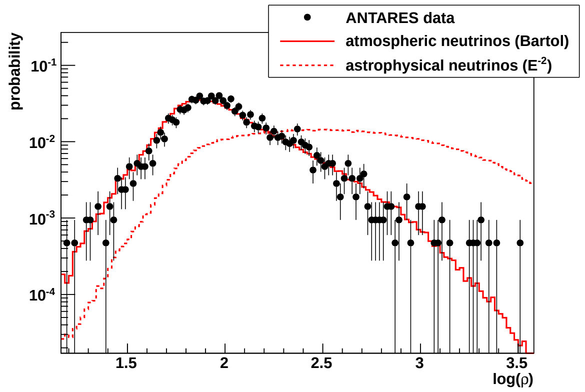
5 Systematic uncertainties

5.1 Energy estimator calibration

The derived energy estimator relies on Monte Carlo simulations for the correspondence between the estimator, i.e. the $\rho \approx \mathrm{d}E/\mathrm{d}X$ values, and the muon (neutrino) energy. If the used simulations do not perfectly describe the real data, systematic biases might be introduced. No significant difference between data and MC in the distributions of the parameters used as input for the energy reconstruction have been found (cf. Sec. 3). The related systematic uncertainty is therefore expected to be reasonably small. In order to quantify the remaining uncertainty, we studied the influence of changes in the Monte Carlo simulations on the energy reconstruction. In an end-to-end approach, a dedicated $\rho \rightarrow E$ calibration (cf. Sec. 2.2) using only a subset (corresponding to data taken in 2008) of a modified Monte Carlo simulation set has been used. Applying this calibration to the simulations described above covering the full period (2007-2011) several potential effects are included. Among them are uncertainties in the charge and time calibration of the detector, different background noise levels, as well as different detector layouts induced by maintenance and (to a lesser extend) hardware failures. From this study, the overall systematic uncertainty due to imperfections of the Monte Carlo simulations has been estimated to be less than 0.1 in $\log(E)$.

5.2 Detector and time evolution

The ANTARES data taking conditions are not stable in time mainly due to changes in the background rate (induced in majority by bioluminescence) and changes in the detector configuration (construction, maintenance, etc.). The reliability of the energy reconstruction algorithm has therefore been studied as function of both contributions. Thanks to the very robust hit selection, which is able to remove the majority of noise induced hits, no strong dependence of the energy reconstruction quality as function of the background rate has been found. On the other hand, due to the very different detector configuration of only 5 active detection lines in 2007, a significant bias of almost 0.5 in $\log(E)$ has been found for that period. It should be noted that the ρ estimator itself is not influenced by this bias and that a dedicated calibration table for that period removes it completely.



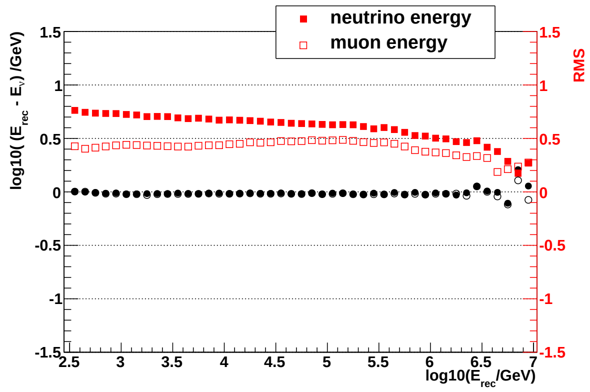


Figure 3: Left plot: Distributions of the ρ parameter showing the good agreement between data (black markers) and Monte Carlo simulations (solid, red line). For illustration the expectation for an astrophysical neutrino flux is also shown (dotted, red line). Right plot: The stability of the mean (black markers) and the evolution of the RMS (red markers) of the difference between reconstructed and true energy as function of the reconstructed energy. Filled (open) markers denote the reconstruction of the neutrino (muon) energy.

5.3 Dependence on quality criteria

Other potential systematic effects might arise when events are selected based on different quality criteria. To study this behaviour a cut variation analysis has been performed. Events have been selected based on the criteria given in Sec. 4 removing only the cut under study one by one. No strong dependence on the reconstructed muon direction nor on the exact value of the quality selection criteria (here: angular uncertainty β and reconstruction quality Λ) is found. The dependence on the muon path length within the fiducial volume (cf. Fig. 1) can be removed by the requirement to have path length $L_\mu > 380$ m as discussed above.

Several dependencies of the energy reconstruction stability and performance on intrinsic parameters have been studied in addition. The quality of the energy reconstruction depends for example on the value of the detection efficiency defined in Eq. 2. No clear evidence for its origin could be determined. The dependency is neither correlated to detector effects nor to the underlying event geometry. As some events are affected by a significant underestimation of the energy, an a-posteriori correction has been developed. This correction is based on a fit to the mean energy bias as a function of the detection efficiency. Applying this correction to the full data set on an event-by-event basis leads to an improvement of the energy resolution by $\log(E) = 0.01$ with respect to the default values obtained in Sec. 4.

5.4 Energy spectrum

The selection of simulated events used for the calibration of the energy estimator is subject to individual choices. The estimator can for example be *trained* on atmospheric muons, atmospheric neutrinos or (as used throughout this paper) on astrophysical neutrinos following an E^{-2} spectrum. Although a dedicated calibration of the energy estimator for each application is highly advised, an uncertainty on the expected energy spectrum of the analysed events will probably remain. To quantify this uncertainty, the energy of neutrino events were reconstructed using the default E^{-2} calibration. They were then weighted to follow a power-law with index $\alpha = -2.2$. The obtained resolution and its energy dependence show only a small systematic bias of about 0.05 and an degradation of the resolution by 0.03 in $\log(E)$. These uncertainties are comparable with the ones introduced by modifications of the Monte Carlo simulations and extending the validity of the calibration in time (cf. Sec.5.1).

6 Summary

We presented an algorithm able to use the deposited energy dE/dX to estimate the energy of muons and neutrinos detected by large scale neutrino telescopes. Applied to data and Monte Carlo simulations of the ANTARES detector the method has been validated and a resolution of $\log(\Delta E) \approx 0.45$ for muons and $\log(\Delta E) \approx 0.7$ for neutrinos has been obtained. The systematic uncertainty has been conservatively estimated to be 0.1 in $\log(E)$ with the main contribution due to the uncertainty in the energy spectrum.

The energy estimation method is mainly limited by the available detection volume. A significance performance increase can therefore be expected by the next generation of neutrino telescopes like KM3NeT [8].

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