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Reconstruction of high energy muon events in IceCube using waveforms

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Abstract:

We present a method to reconstruct the geometry and energy of high energy muon tracks in IceCube. Through a log-likelihood optimization procedure, an event hypothesis is obtained by maximizing the agreement of the expected amount of light (as function of time) in the optical modules with the shapes of the pulses recorded in the optical modules. This reconstruction method aims to use all information contained in the waveforms recorded in the IceCube digital optical modules (DOMs), by comparing those waveforms directly with the expected arrival time distribution of Cherenkov photons at the DOM after emission from a hypothetical track, taking into account the optical properties of the South Pole ice. We expect that this method will be effective in particular for highly energetic events in which a significant fraction of the DOMs records many photo-electrons. Currently, for simulated events within an energy range of $100\,\mathrm{TeV}$ to $32\,\mathrm{PeV}$ which were reconstructed as throughgoing, we obtain an energy resolution of 0.34 in $\mathrm{Log}(E/\mathrm{GeV})$ and an angular resolution of $0.62°$.

Introduction

The IceCube telescope is being deployed in the Antarctic ice with its main goal to detect high energy neutrinos arriving from astrophysical sources. Nearly one third of the detector is installed and currently operational [1]. When fully deployed, the instrumented volume will be approximately $1\,\mathrm{km}^3$.

When a neutrino interacts in the ice in or near the detector, it produces a track or cascade signature. Some of the Cherenkov light emitted by the charged lepton and secondary charged particles triggers the DOMs. A DOM digitizes the signal from a $10\,\mathrm{inch}$ photo-multiplier in two ways: with an analog transient waveform digitizer (ATWD) and with a fast analog to digital converter (fADC) [2].

The main purpose of the ATWD is to record precise timing information of photons arriving in DOMs relatively close to the track or cascade. Therefore, it reads the same signal in 3 channels operating on different gains. Each channel has up to 128 bins with a bin witdh of $3.6\,\mathrm{ns}$. The main purpose of the fADC is to measure pulses with a wider time distribution from a further away track or cascade. It has 256 bins with a bin width of $25\,\mathrm{ns}$, giving a total time window of $6.4\,\mu\mathrm{s}$.

Given that the IceCube neutrino observatory records the full waveform information, a new likelihood reconstruction technique to exploit the full waveform information is the goal of the research described in this paper. Conventional reconstruction techniques [3] ported to IceCube from its predecessor, AMANDA, do not use the complete waveform. This is a reflection of the original AMANDA data acquisition system which recorded only the leading edge time of the pulse, the total charge of the pulse, and the total time over threshold of the pulse. These conventional reconstruction techniques in IceCube utilize this information by extracting pulse shapes from the ATWD or fADC waveforms and reconstruct a cascade or a muon hypothesis based on this information.

In this paper, we focus on the likelihood reconstruction of high energy muon tracks arising from extremely high energy (EHE) neutrinos with energies up to 10^{11} GeV. EHE neutrinos should be produced when EHE cosmic rays interact with the cosmic microwave background [4]. The significant background due to atmospheric muons presents a major challenge, however. Since the zenith and energy distributions are different for signal and background, good geometry and energy reconstruction are vital for signal detection.

We hope that with the waveform-based event reconstruction method a significant improvement in sensitivity can be achieved for events at a wide energy range from $\sim 10\,\mathrm{TeV}$ up to highest energies, $\sim\,\mathrm{EeV}$. At energies above $1\,\mathrm{PeV}$ we expect to increase the sensitivity by effectively reconstruction the energy of non-contained events.

Method

We define a function which gives the likelihood that the observed waveforms in the DOMs are the result of a given muon track. Using a standard minimizer algorithm, the track's position, direction and energy are found for which the likelihood has a maximum.

Expected photon arrival time distribution at a single DOM

A crucial element in the likelihood function is the description $\mu(t)$ of the expected number of photo-electrons as a function of time in a given DOM for a given muon track. This description consists of the expected total number of photo-electrons μ_{tot} together with a probability density function (PDF) $p(t)$ of the arrival time distribution of a single photon: $\mu(t) = \mu_{tot} \cdot p(t)$.

The μ_{tot} and PDF depend on the energy, direction, and the distance of the track to the DOM, the relative orientation of the DOM with respect to the track, and the optical properties of the ice between the track and the DOM.

At energies of a few hundred TeV and higher, most of the Cherenkov light is not emitted by the muon itself, but by its many secondaries and by the stochastic showers. For our reconstruction of

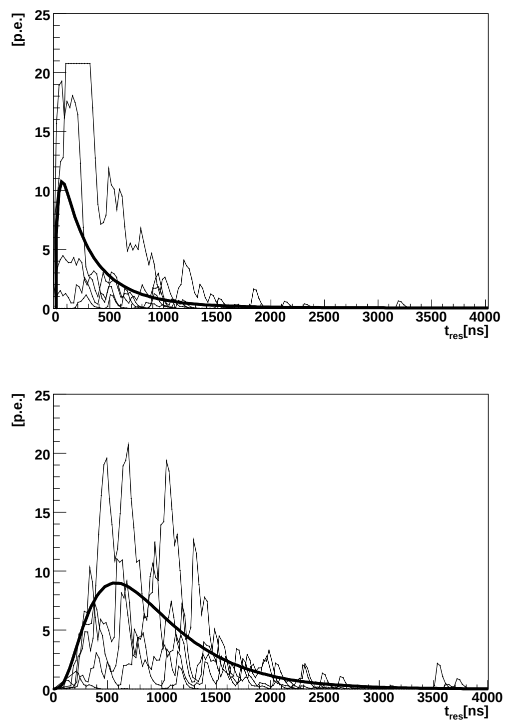

Figure 1: Comparison of the expected photo-electron distribution $\mu(t)$ (thick line) from photonics tables with some actual waveforms from the full MC simulation of high energy muons (thin lines). Upper figure: $1\,\mathrm{PeV}$ at $53\,\mathrm{m}$, lower figure: $100\,\mathrm{PeV}$ at $147\,\mathrm{m}$.

a high energy muon track, we assume that the muon track with stochastic showers can be approximated by an "infinite cascade" which is a string of equidistant average showers each with an energy deposit corresponding to the dE/dX energy loss of the track in the ice.

For the results in this paper, we took μ_{tot} and the PDF from a table generated using the "photonics" light propagation code [5]. An alternative approach uses a parametrization of the average waveforms obtained from the full IceCube simulation.

Fig. 1 shows the comparison between the expected photo-electron distribution $\mu(t)$ as obtained with photonics and individual waveforms as obtained in the full MC simulation.

It should be remarked that the individual waveforms may resemble the expected average waveform only at very high energies and in DOMs close enough to the track. In most events, the individual waveforms in various DOMs will look different, as shown in Fig. 1. First, individual stochastics near the DOMs may produce fluctuations beyond the statistical (Poissonian) fluctuations from the average as modeled by the infinite cascade approximation. Second, when the $\mu(t)$ times the width a of a single photoelectron pulse is less than 1, then the of course the individual waveforms of the occasional individual photoelectrons will not follow that low PDF.

Poissonian likelihood for waveforms

The conventional reconstruction strategy described in the introduction works well for lower energy muon events in which the total charge corresponds to only a few photo-electrons. High energy muon events on the other hand are characterized by a large amount of deposited light and therefore produce wide, complicated waveforms with many photo-electrons. Reconstructing the geometry of a high energy muon track would benefit from the complete waveform information, as the width of the observed waveforms scales with the distance between the muon track and the DOM. A likelihood reconstruction of the muon energy would also require the complete waveform in order to measure the total amount of light deposited in the IceCube detector since this correlates with the energy of the muon.

The likelihood function using the complete waveform is formulated as follows. What is the probability of observing a waveform $f(t)$ given an expected photo-electron distribution $\mu(t)$? The waveform $f(t)$ is measured from the ATWD or the fADC, and the expected photo-electron arrival distribution is given by the PDF. The expected photo-electron arrival distribution depends on the hypothesis parameters, namely the geometry $\vec{x}$ (position of the muon at $t = t_0$ and its direction) and the energy, E. If you bin the waveform $f(t)$ into K bins, the probability of observing n_i photons in the ith waveform bin given an expectation of μ_i photons in the ith bin is given by Poissonian statistics. The overall probability for a single OM is given by the product over all waveform bins:

$$P(f(t)|\vec{x}, E) = \prod_{i=1}^{K} \frac{e^{-\mu_i}}{n_i!} \mu_i^{n_i} \tag{1}$$

Taking the log of the Poissonian probability gives us:

$$\begin{aligned} \log P(f(t)|\vec{x}, E) \quad &= \quad \sum_{i=1}^{K} \left(n_i \log \frac{\mu_i}{\mu_{tot}} \right) \\ &+ N_{pe} \log \mu_{tot} - \mu_{tot} \end{aligned} \tag{2}$$

The first term is a sum over all waveform bins. Each term in the sum $n_i \log \frac{\mu_i}{\mu_{tot}}$ corresponds to the normalized timing probability of observing a photo-electron in the ith waveform bin weighted by the number of observed photo-electrons in the ith bin.

We evaluate Eq. 2 for all DOMs in the ice and sum these values as our log-likelihood function which we then maximize with respect to the free parameters of the track. This amounts to fitting the shape of the PDF to the measured waveform. This allows the reconstruction of not only the geometry of the muon, but also its energy.

One feature that needs to be addressed is the issue regarding the saturation of the waveform which the likelihood formula does not take into account. Currently, saturation is taken into account by simply truncating both the PDF and the measured waveform at some level close to the actual saturation level of the hardware, while sticking to the formalism of Poissonian statistics.

Fitting strategy

When reconstructing the muon track, there are in general six free parameters to fit (the vertex, direction, and the energy). Fitting the geometry and energy separately in three stages turns out to be more efficient than fitting them all at once. We seed the first stage of the reconstruction with a first guess of the geometry and the energy and proceed to fit the geometry only (five free parameters). We then seed the second stage with this result, fitting the energy only (one free parameter). Finally, we use this second stage result to seed a third fit, which refits the geometry again (five free parameters).

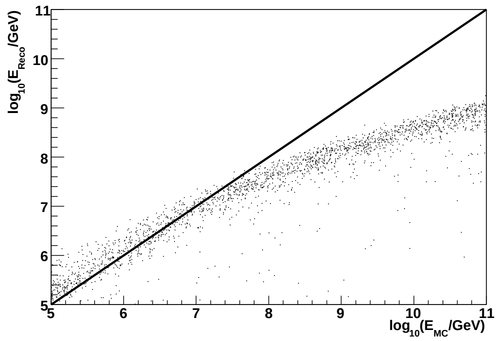

Figure 2: Reconstructed muon energy versus simulated energy for reconstructed tracks that go through the IceCube detector (see text). The diagonal line $E_{reco} = E_{true}$ is added to guide the eye.

Results

The energy reconstruction results are shown in Fig. 2 for a MC event sample simulated with an E^{-1} spectrum and an energy range from $10\,\mathrm{TeV}$ to $100\,\mathrm{EeV}$ with 4π coverage in the full 80-string IceCube geometry. Only reconstructed throughgoing muon tracks are selected, which are muon tracks whose point of closest approach to the geometrical center of the IceCube detector is within the IceCube array.

At energies above $\sim 30\,\mathrm{PeV}$, the reconstructed energy is systematically low due to saturation in the DOMs, which is currently not taken into account. The slope of the distribution for energies below $30\,\mathrm{PeV}$ may be improved by adjusting the "infinite cascade" model, in particular the relation between the energy of the muon track and the energy in an average shower of the infinite cascade. For energies below $30\,\mathrm{PeV}$, approximately 31% of the events are reconstructed as throughgoing.

For throughgoing muon tracks and $E_{MC} < 30\,\mathrm{PeV}$, the angular resolution (defined as the median of the distribution of angular differences of the reconstructed and simulated muon tracks) is found to be $0.62°$. Our obtained energy resolution is 0.34 in $\mathrm{Log}(E/\mathrm{GeV})$. With the traditional AMANDA style reconstruction about 35% of the events are reconstructed as throughgoing, with an angular resolution of $0.63°$.

Outlook

The waveform based reconstruction as currently implemented performs reasonably well. With a sample of simulated high energy events, we obtain an angular resolution comparable or better than conventional reconstruction methods.

We have identified several aspects of the algorithm and its implementation which can still be improved, including a proper way to use the information of saturated DOMs. This should further improve the energy resolution (currently 0.34 in $\mathrm{Log}(E/\mathrm{GeV})$) and extend the energy range beyond 1EeV. The results of this paper are only for throughgoing muon tracks; we hope to present similar results for high energy non-contained events as well.

The method is in principle not limited to track-like events; it can be applied to events of any signature, such as showers and possibly also muon bundles.

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