Muon energy reconstruction and atmospheric neutrino spectrum unfolding with the IceCube detector

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Abstract: Data collected during the year 2006 by the first 9 strings of IceCube can be used to measure the energy spectrum of the atmospheric muon neutrino flux. Atmospheric neutrinos are the irreducible background in the search for high energy cosmic neutrinos and a useful calibration source of events. They can be used to probe the high energy hadronic interaction models in regions where accelerators could not provide direct measurements. A full reconstruction of the neutrino-induced muon tracks provides both directional and energy information. The decoupling of calculating the photon density along the muon track from the energy calibration with the simulated data leads to an improved stability of the result. This quantity can be used to calculate the energy spectrum, which is reconstructed by using unfolding techniques, since the event-by-event reconstruction is very inefficient due to bin-to-bin migrations. We will discuss the unfolding procedure to be applied to data from the 9-string configuration of IceCube.

Motivation

The IceCube collaboration is building a cubic kilometer neutrino telescope in the Antarctic ice. Since neutrinos are neutral, stable and weakly interacting, they are a unique probe to study the Universe at high energies and IceCube will be the most powerful tool available for observing them. When completed by 2011, it will consist of 80 strings with 4800 photomultipliers which will detect the Cherenkov light emitted by the relativistic muons produced in the CC interactions of high-energy neutrinos. IceCube can also observe the cascades produced by CC ν_e and ν_τ interactions and NC interactions of any flavor.

During the Austral summer 2006-07, a total of 22 strings have been already deployed and are smoothly working. In this paper we will study the data corresponding to the previous season, when 9 strings were installed.

The scientific output of neutrino astronomy is very wide, including the search of dark matter and the observation of astrophysical neutrinos from a large variety of sources (gamma-ray bursts, active galactic nuclei, microquasars, etc.) Therefore, it is very important to study the background due to neutrinos from decay of pions and kaons produced by the interaction of cosmic rays in the atmosphere. Experiments like AMANDA [1] have measured the neutrino atmospheric spectrum up to $\sim$100 TeV and IceCube will be able to explore the region where the prompt neutrino component (due to charmed meson decays) will dominate. The atmospheric muon background can be severely reduced by selecting only up-going events and imposing restrictive constrains in the quality of the reconstructed track. On the other hand, atmospheric neutrinos cannot be rejected in this way, so it is important to understand well the rates and spectrum of this background.

A detailed study of the rates of the 9-string configuration of IceCube can be found in [2]. In this paper, we will focus on the reconstruction of the energy spectrum. This spectrum cannot be reconstructed by just piling-up the energy of individual events because of two factors. First, the energy resolution is limited because we only see part of the muon energy (which in turn is only part of the neutrino energy) and because the muon energy loss is stochastic. Second, the spectrum falls very quickly with energy (as $E^{-3.7}$), so the events for which the energy is overestimated would bury the events at higher energy, distorting the resulting spectrum. In order to overcome this problem, a different approach is needed: the unfolding techniques.

The structure of this paper is as follows. In the next section, we will describe the calculation of the variable used for the unfolding. This variable has to be correlated with the neutrino energy with the lowest possible spread. Among the different variables that have been studied (number of hit optical sensors, total charge, reconstructed energy, etc.) the best results are obtained with the reconstructed energy (in particular with the muon reconstructed energy at the point of closest approach to the center of gravity of hits in the event). In the following section we make a brief description of the unfolding procedure, explaining how the robustness of the method is included. Finally, we show the resulting unfolded spectrum.

Energy reconstruction technique

As a muon travels through ice, it alone (i.e., "bare" muon) emits about $3 \cdot 10^4$ Cherenkov photons in the spectral range visible to the detector per each meter of its track. In addition, the knock-on electrons, bremsstrahlung, electron pairs, and photonuclear interactions caused by the muon traveling through ice, generate short cascades along the muon track [3]. Particles created in such cascades also emit Cherenkov radiation, increasing the "effective length" of the muon (which determines the total number of Cherenkov photons using the above factor) by the amount proportional to the energy of the cascade, on average by about 4 m$\cdot$ E/GeV. The number of additional Cherenkov photons emitted by the passing muon due to cascades created along its path is therefore proportional to the total energy deposited in form of such cascades. In a well-known approximation of the muon energy losses, $dE/dx = a + b \cdot E$, the second term is largely due to just such energy deposits. Above the critical energy ($\sim$ 1 TeV), the second term begins to dominate the energy losses, and the total number of Cherenkov photons left by a muon per unit length of the muon track becomes proportional to its energy:

$$N_c = 3{\cdot}10^4 \mathrm{m}^{-1}(1.22{+}1.36{\cdot}10^{-3} E/[\mathrm{GeV}]) \quad (1)$$

This "photon density" along the muon track enters naturally into the muon track reconstruction through a term in a log likelihood function, which describes how well the number of photons observed at a distance d from the track is described by the flux function. The flux function is easily computed in the vicinity of the track, before the scattering of light alters the original direction of photons in the Cherenkov cone around the track. At large distances one may use the diffusive approximation since the photons observed there have sustained many direction-altering scattering events. In the intermediate distance region these approximations are stitched together with a function, chosen to describe all 3 regions. The shape of the function was inspired by the eikonal small-angle scattering approximation of light that may be used in low-scattering media, e.g., water. The chosen flux function was verified against data and was found to perform extremely well.

The photon density along the muon track thus becomes the 6th parameter in addition to two angles and 3 parameters describing a point in space and time along the muon track, against which the likelihood function is minimized. One may then calculate the energy by either inverting equation (1) or performing the Monte Carlo study of the correlation of the calculated photon density and energy (see Figure 1). The second approach additionally results in a smearing matrix, which can then be used for spectra unfolding (next section). In all cases the energy of the muon is taken at the point of closest approach to the center of gravity of hits left by the muon in the detector (which yields better energy estimates than alternatives).

Figure 2 shows the resolution of the energy reconstructed with the method described here and with methods based on the calculation of the number of hit optical channels (N_{ch}) and total charge (Q_{tot}). For the isotropic fluxes in the energy range of $10^{4.4} - 10^{7.4}$ GeV reconstruction precision of 0.3 in $\log_{10}$(E [GeV]) is achieved. This is close to

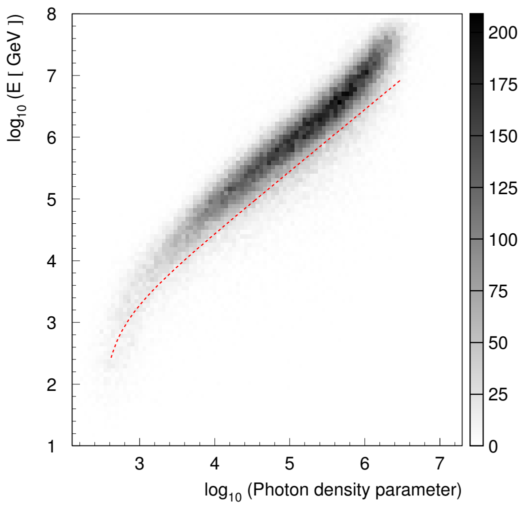

Figure 1: Correlation of true muon energy and reconstructed photon density parameter (photon density N_c times optical sensor effective PMT area). Red line demonstrates the result of applying eq. (1). It overestimates the value of the photon density parameter somewhat when compared to the detailed simulation.

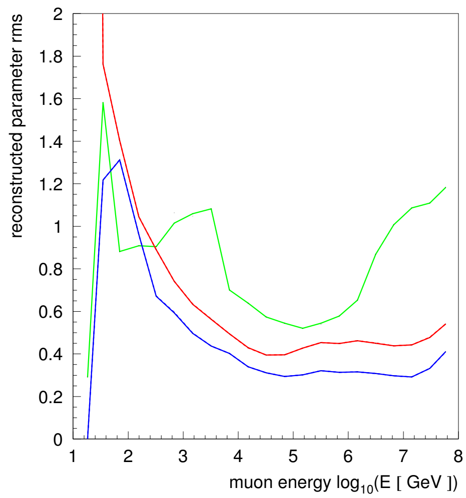

Figure 2: Energy reconstruction precision: blue (lowest curve) for the photon-density-based approach of this paper, red for the Q_{tot} and green (highest curve) for the N_{ch}-based calculations.

the theoretically achievable (due to uncertainty related to stochastic nature of energy losses). For the atmospheric neutrino fluxes this energy range increases to $10^{3.6} - 10^{7.6}$ GeV. At low energies resolution worsens due to reduced dependence of muon energy losses on muon energy below the critical energy. This may potentially be improved by using the observed muon track length as an additional energy-correlated parameter. At high energies one expects the nearby optical sensors to be saturated, leading to increased systematic uncertainties and, in turn, to reduced energy reconstruction precision. This will likely improve with more detailed corrections of the saturated behavior taken in the account.

Unfolding procedure

There are different unfolding methods used in high energy physics. Previous studies of the atmospheric neutrino unfolding have been done both for AMANDA data [4, 5] and ANTARES simulation [6]. For this analysis we have chosen the Singular Value Decomposition algorithm [7], since it is robust, efficient and easy to implement. The problem of unfolding can be expressed, in matrix notation, by the expression $\hat{A}y = b$, where $\hat{A}$ is the so-called smearing matrix (which has to be generated by Monte Carlo), y is the spectrum we want to measure (in this case, the neutrino energy), and b is the experimental observable. Inverting the smearing matrix does not give a useful solution because of the effect of statistical fluctuations, which completely spoils the result. The SVD algorithm is based on the decomposition of $\hat{A}$ as $\hat{A} = USV^T$, where U and V are orthogonal matrices and S is a non-negative diagonal matrix whose diagonal elements are called "singular values". It can be shown that this decomposition allows to easily identify the elements of the system that contribute to the statistical fluctuations but provide useful information. Thus, these elements can be filtered out in order to obtain a smoother solution.

Another interesting point of this method is that in practice we do not try to solve directly the spectrum, but the deviations from a reasonable assumption. This also helps to reduce the effect of statistical fluctuations.

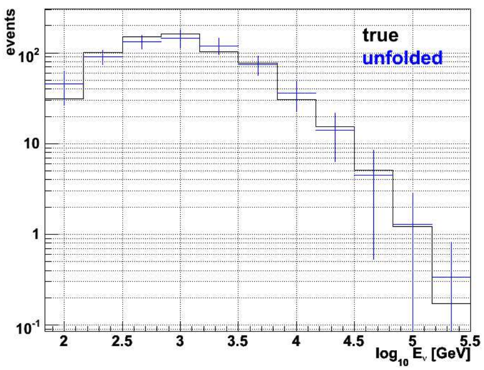

Figure 3: True (black line) and unfolded (blue crosses) spectra. It can be seen that the agreement between both distributions is good (preliminary). Errors are not statistical, but they contain global unfolding uncertainty.

Results and discussion

The event selection used in this work are based on the ones used for the atmospheric neutrino rates analysis [2]. The variables to perform such a selection are the same and the values have been relaxed somewhat in order to increase the statistics: N_{dir} (number of unscattered photons) ≥ 8, L_{dir} (length of the track) > 200 m and θ (zenith angle) > 92 deg. These cuts should still reject most of the background contamination, which is still under study. In order to check that the simulation is under control, we have compared the simulated and real distribution of several variables, finding good agreement.

We have checked the robustness of the unfolded results in two different ways: 1) the spectral index used when creating the smearing matrix. In this case, the spectral index is $\gamma = -2$, far from $\gamma = -3.7$, thus different enough. 2) the initial assumption for the solution of the system. For this issue, we have used different shapes within a wide interval and shown that the algorithm converges towards the expected solution. Figure 3 compares the true (generated by Monte Carlo) and unfolded distributions, showing a good agreement between both (preliminary result).

Conclusions

The atmospheric neutrino spectrum is an important result both for its intrinsic physics interest and because atmospheric neutrinos are the main source of background in most of the analysis in neutrino telescopes. In order to reconstruct this spectrum we have to use unfolding techniques. In this paper we have described how to reconstruct the muon energy (at the point of closest approach to the center of gravity hits in the event), which is the variable with the best correlation with the neutrino energy. Finally, the unfolded spectrum is obtained, showing also that the algorithm works properly when compared with Monte Carlo.

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