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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 neutrino flux. Atmospheric neutrinos, an important scientific output by itself (for instance, to understand the high-energy hadronic interaction models), are also fundamental in order to check the performance of the detector and to estimate the background for other analysis. The muon energy is one of the parameters that results from reconstruction together with other muon track parameters. 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. The spectrum is reconstructed by using unfolding techniques, since the event-by-event reconstruction is very inefficient due to bin-to-bin migrations. We will show the atmospheric neutrino spectrum measured in 2006 by the 9-string configuration of IceCube.

Motivation

The IceCube collaboration is building a cubic kilometer neutrino telescope in the Antarctic ice. Being neutral, stable and weakly interacting, neutrinos 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 lines with 4800 photomultipliers which will detect the Cherenkov light induced by the relativistic muons produced in the CC interactions of high-energy neutrinos (other signatures, as cascades, are also possible).

After the season 06-07, a total of 22 lines have been already deployed and are smoothly working. In this paper we will study the data corresponding to the previous season, when 9 lines were installed.

The scientific output of neutrino astronomy is very wide, including the search of neutralino and the observation of astrophysical neutrinos from a large variety of sources (gamma-ray bursts, active galactic nuclei, microquasars, etc.) Atmospheric neutrinos are also one of the main topics for two reasons. First, because of its intrinsic interest to understand the production of secondary cosmic rays in the atmosphere. Experiments like AMANDA have extended the neutrino atmospheric neutrino spectrum up to $\sim$100 TeV and IceCube will be able to explore the region were the prompt neutrino component will dominate. Second, atmospheric neutrinos are the main source of background for the other analysis mentioned before. 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, but in order to ensure that the impact of atmospheric neutrinos is low enough we have to understand well its rates and spectrum.

A detailed study of the rates of the 9-line configuration of IceCube can be found somewhere else in these proceedings [1]. In this paper, we will focus on the reconstruction of the spectrum. This spectrum cannot be reconstructed by just piling-up the energy of individual events for the combination 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 very stochastic. Second, the spectrum falls very quickly with energy (as $E^{3.7}$), so the events for which the energy is overestimated will 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. First, we will describe the calculation of the variable used for the unfolding. This has to be a variable correlated with the neutrino energy and the lower possible spread. Among the different variables that have been studied (number of hit DOMs, 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 the detector). In the following section we describe how this variable is calculated. In the next 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 $3 \cdot 10^4$ Cerenkov 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, each start short cascade-like events along the muon track. Particles created in such cascades also emit Cerenkov radiation, adding to the "effective length" of the muon with a term proportional to the energy of the cascade, on average by about 4 m$\cdot$ E/GeV. So the number of additional Cerenkov photons emitted by the passing muon due to cascades created along its path is 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. So, above the critical energy ($\sim$ 1 TeV), the second term begins to dominate the energy losses, and the total number of Cerenkov photons left by a muon per unit length of the muon track becomes proportional to the energy of the muon:

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

Such "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 Cerenkov cone around the track, and in the far region, to reach which photons must have sustained many direction-altering scattering events, i.e., where one may use the diffusive approximation. 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 so-chosen flux function was verified against data and was found to perform extremely well.

In this approach the photon density along the muon track 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 calculation of 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).

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

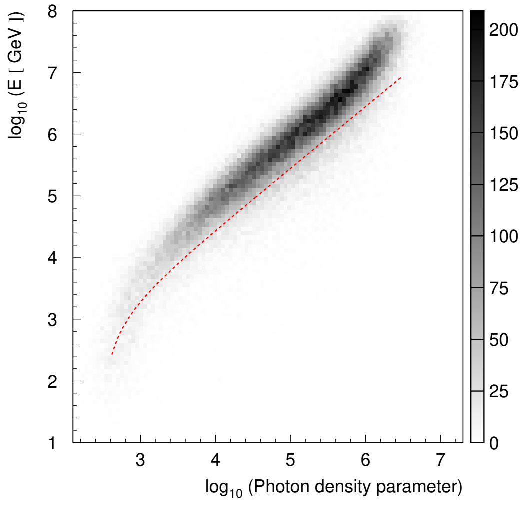

Figure 1: Correlation of true energy and reconstructed photon density. Red line demonstrates the result of applying eq. (1)

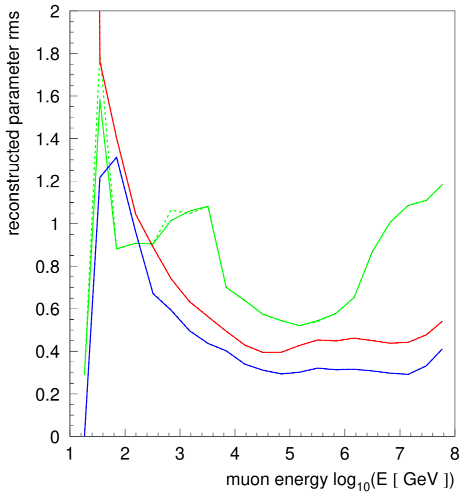

Figure 2: Energy reconstruction precision: blue (lowest curve) for the photon-density-based approach of this paper, red for the Q_{tot} and green (highest curve) for the N_{ch}-based calculations

close to the theoretically achievable (due to uncertainty related to stochastic nature of energy losses). For the atmospheric neutrino fluxes this energy range increases to 3.6 – 7.6. At the low end resolution gets worse due to reduced dependence of muon energy losses on muon energy below the critical energy. At the high end one expects the nearby DOMs to be saturated, which leads to increased systematic uncertainties and, in turn, to the reduction in energy reconstruction precision. This may improve in the future as we implement more detailed corrections of the saturated behavior.

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 [2, 3] and ANTARES simulation [4]. For this analysis we have chosen the Singular Value Decomposition algorithm [5], 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 obtain (in this case, the neutrino energy), and b is the observed magnitude. 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 identify easily 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 the statistical fluctuations.

Results and discussion

The quality cuts used in this work are based of the ones used for the atmospheric neutrino rates analysis [1]. 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}

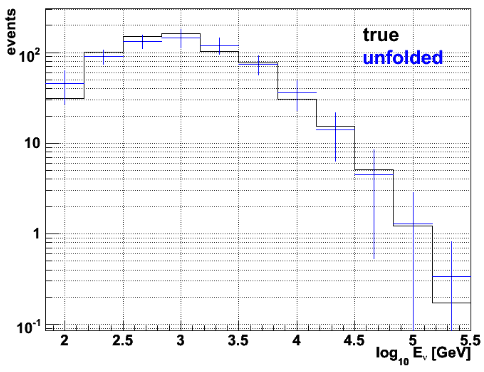

Figure 3: True (black line) and unfolded (blue crosses) spectra. It can be seen that the agreement between both distributions is good.

(number of direct photons) ≥ 8, L_{dir} (length of the track) > 200 and $\theta > 92$ deg. The level of purity of the final sample is 98%.

In order to check that the simulation is under control, we have compared the simulated and real distribution of several variables, finding good agreement.

In these analysis, it is also important to check the robustness of the method with respect to the prior assumptions. These are basically two: 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.

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 the detector), 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.

References

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