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Measurement of the atmospheric muon neutrino energy spectrum with IceCube in the 79- and 86-String configuration

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Abstract. IceCube is a neutrino telescope with an instrumented volume of one cubic kilometer. A total of 5160 Digital Optical Modules (DOMs) is deployed on 86 strings forming a three dimensional detector array. Although primarily designed for the detection of neutrinos from astrophysical sources, the detector can be used for spectral measurements of atmospheric neutrinos. These spectral measurements are hindered by a dominant background of atmospheric muons. State-of-the-art techniques from Machine Learning and Data Mining are required to select a high-purity sample of atmospheric neutrino candidates. The energy spectrum of muon neutrinos is obtained from energy-dependent input variables by utilizing regularized unfolding. The results obtained using IceCube in the 79- and 86-string configuration are presented in this paper.

1. Introduction

IceCube is a neutrino detector array located at the geographic South Pole. Its 5160 Digital Optical Modules (DOMs) are deployed on 86 strings, at depths between 1450 m and 2450 m forming an instrumented volume of 1 km^3 [1]. The DOMs are used to detect neutrinos via Cherenkov radiation initiated by their interaction products. Event properties, such as energy and direction are reconstructed from geometrical, timing and charge information obtained from the DOMs.

IceCube can be used to study neutrino spectra. The ν_μ energy spectrum is believed to consist of three major components. The first one is conventional atmospheric neutrinos originating from the decay of pions and kaons. The second component are prompt atmospheric neutrinos, which originate from the decay of charmed mesons. Both components are expected to follow a power law of the form $E^{-\gamma}$ and can be distinguished from their spectral indices [2]. Although the atm. ν_μ spectrum has been measured by various experiments, including Super-Kamiokande [3], ANTARES [4] and IceCube [5, 6], it is still subject to large uncertainties, especially at high energies [7]. Neutrinos from astrophysical sources [8] contribute to the spectrum as a third component. This component is expected to cause a flattening of the ν_μ energy spectrum at high energies.

This paper presents a model-independent measurement of ν_μ energy spectrum with IceCube in the 79- and 86-string configuration. The measurement determines the sum of all possible contributions to

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Table 1. Cuts placed on different variables prior to training and testing the Random Forest. Only events to which the conditions of the cuts in this table apply were kept in the sample for further analysis.

IceCube-79		IceCube-86	
Cut Variable	Cut Value	Cut Variable	Cut Value
θ_{Zenith}	$\geq 86^\circ$	θ_{Zenith}	$\geq 86^\circ$
v_{Lepton}	$\geq 0.1\,\text{c}$	l_{Track}	$\geq 200\,\text{m}$
—	—	Empty Hits	$\leq 400\,\text{m}$

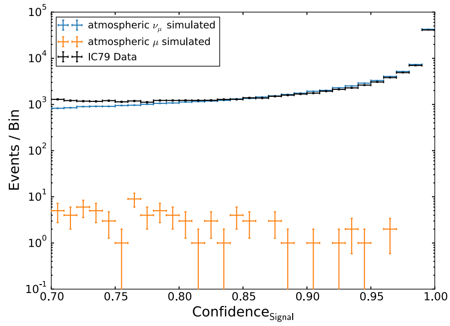

Figure 1. Confidence c for IceCube-79 in the region of the final selection. A good agreement between data and simulation is observed.

the spectrum. It is organized as follows: the selection of neutrino candidates is described in Sect. 2, whereas the unfolding of the ν_μ energy spectrum is addressed in Sect. 3. Section 4 concludes the paper with a discussion of the results.

2. Event selection

In IceCube muon neutrinos are detected via their interaction products – neutrino-induced muons. The background consists of atmospheric muons, entering the detector from above. At the starting level of this analysis the signal-to-background ratio is 10^{-3}. Therefore, a dedicated event selection is required in order to select neutrino candidates. The event selection is based on Machine Learning and carried out in a stepwise procedure.

In the first step we apply straight cuts to achieve a rejection of background events and a reduction of the required CPU-resources. The cuts placed on the different variables are summarized in Table 1. The cut on the zenith angle θ_{Zenith} removes a large portion of the muon background. The remaining muon events are falsely reconstructed as upward going and significantly harder to reject.

A Random Forest [9] is used to also reject those falsely reconstructed atmospheric muons. Simulated events generated with CORSIKA [10] and simulated neutrino events generated with NuGen [11] were used for training and testing. The testing was carried out in a five-fold cross validation. Input variables to the forest were selected using the Maximum Relevance Minimum Redundancy (MRMR) algorithm [12]. The stability of the variable selection was validated in a cross validation-like procedure [6, 13]. A Random Forest utilizes an ensemble of decision trees. The final output is generally referred to as confidence c and obtained as an average over the classification c_i of the individual trees:

$$c = \frac{1}{n_{\text{trees}}} \sum_{i=1}^{n_{\text{trees}}} c_i. \tag{1}$$

Figure 1 exemplarily shows the output of the Random Forest for the data sample obtained with the 79-string configuration of IceCube. Simulated atmospheric muons are shown in orange, simulated

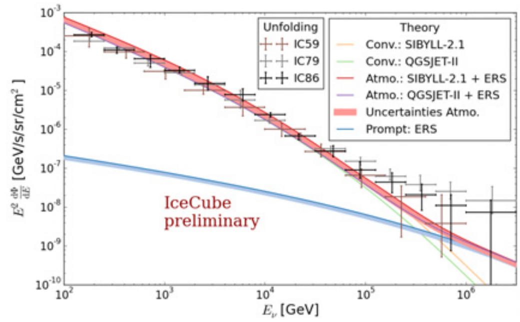

Figure 2. Atmospheric neutrino spectra obtained for the 79- and 86-string configuration of IceCube, compared to theoretical predictions obtained from two hadronic interaction model (SYBILL-2.1 [15] and QGSJET-II [16]) and the prompt flux prediction by Enberg et al. (ERS) [17].

atmospheric ν_μ in blue. Experimental data is depicted in black. A good agreement between experimental data and simulation is observed.

As a final selection criterion, an additional cut is placed on the output of the Random Forest. A cut at a confidence of $c \geq 0.92$ was used for the 79-string configuration. To increase the statistics of the event sample a two-dimensional cut is used for IceCube-86. This 2D-cut is simultaneously applied on the Random Forest output c and the estimated energy of the secondary muon. For $E_\mu \geq 10^4$ GeV events with $c < 0.7$ were rejected, whereas events with $c < 0.87$ were rejected for $E_\mu < 10^4$ GeV.

The event selection yielded a total of 66,885 neutrino candidates in 319.6 days of detector lifetime at an estimated background contamination of 330 ± 200 atmospheric muons for IceCube-79. For IceCube-86 92,060 neutrino candidates were obtained in 320.2 days of detector lifetime at an estimated background contribution of 410 ± 220 background muons.

3. Spectrum unfolding

The energy of the incident neutrino is not directly experimentally accessible. Therefore, it has to be inferred from energy-dependent variables and energy estimators. Furthermore, the production of secondary muons from neutrinos is governed by stochastical processes. Thus, an unfolding is required to reconstruct the ν_μ energy spectrum. Mathematically this is described by the Fredholm integral equation of first kind:

$$g(y) = \int_a^b A(x, y) f(x) \mathrm{d}x. \tag{2}$$

In Eq. (2) the energy distribution of the incident neutrino is denoted by $f(x)$ and $g(y)$ is the distribution of an energy-dependent observable. $A(x, y)$ represents the response function, which includes physics of muon production as well as muon propagation in ice and the limited resolution of the detector.

In this work Eq. (2) is solved using the software TRUEE [14]. TRUEE allows for the use of up to three input variables and the ν_μ spectrum is obtained in a maximum likelihood fit. In this work the estimated length of the muon's track, the number of direct photons and the estimated energy of the neutrino-induced muons were used as input variables for both detector configurations. A high correlation with energy was observed for all three input variables. For details on the unfolding of atmospheric $\nu_\mu$energy spectra and unfolding in general, we refer to [6] and [14].

4. Discussion

The atmospheric ν_μ energy spectra obtained with IceCube in the 79- and 86-string configuration are shown in Fig. 2. The theoretical flux predictions obtained for two hadronic interaction models (SYBILL-2.1 [15] and QGSJET-II [16]) are depicted together with the expected prompt flux according to the model by Enberg et al. (ERS) [17]. The spectrum obtained using IceCube in the 59-string configuration (brown) is shown for comparison [6]. The red shaded area visualizes the uncertainty of the theoretical flux predictions [7].

A flattening of the overall spectrum is observed for neutrino energies $E_\nu \geq 10^{5.3}$ GeV. This flattening is a clear deviation from the assumption of a solely atmospheric contribution to the overall ν_μ energy spectrum. It is attributed to a flux of high energy neutrinos from astrophysical sources. The observed excess is fully compatible with the recent observation of high energy astrophysical neutrinos by IceCube [8].

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