Atmospheric Muon Spectrum from Catastrophic Energy Losses in IceCube

THE ICECUBE COLLABORATION[1]
[1]*See special section in these proceedings*

Abstract: While the primary purpose of IceCube is the search for high-energy astrophysical neutrinos, the overwhelming majority of events is caused by downgoing cosmic-ray induced muons. This provides a high-statistics data set which can be used for both detector calibration and supplemental physics investigations. In this work, we present a method to identify TeV-scale catastrophic energy losses along muon tracks and its application to the separation of single high-energy muons from large-multiplicity bundles which dominate the event sample above the horizon at high energies. The information can be used to derive the single-muon energy spectrum at all zenith angles up to energies of hundreds of TeV. We demonstrate that our measurement is sensitive to a cutoff of the proton spectrum at the cosmic ray knee and potentially to the prompt lepton flux caused predominantly by decay of charmed hadrons in atmospheric CR interactions.

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1 Introduction

In recent work on high-energy atmospheric muon fluxes, it was pointed out that second-generation astrophysical neutrino detectors such as IceCube should be able to substantially extend the energy range of muon energy spectrum measurements and hence address various important open problems in cosmic-ray physics. These include verification of hadronic interaction models, primary composition at PeV energies and prompt contributions to the lepton flux [1].

From an experimental perspective, the main challenge in the measurement of the muon energy spectrum is limited spatial resolution due to the sparse instrumentation of the detector. With a minimum separation of 17 meters between Digital Optical Modules (DOMs) in IceCube, resolution of individual muons within a shower is usually impossible. Previous measurements [2, 3] took advantage of the shorter range of large-multiplicity muon bundles compared to individual high-energy muons during passage through matter to measure the muon spectrum at large slant depths near the horizon. The limited angular resolution of the detector and background from up-going atmospheric neutrinos mean that the range of this technique is limited to values up to approximately 100 TeV. Furthermore, the muon spectrum can in this way only be measured in an angular region where the relative contribution from prompt interactions is lowest, excluding investigation of this flux component for practical purposes.

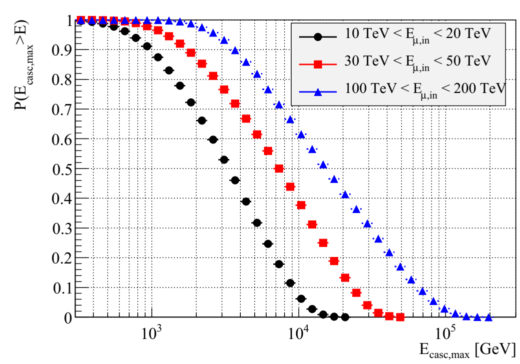

Figure 1: Probability for a stochastic loss above a given energy to occur within the detector volume, for three typical muon energy ranges. The simulation was performed using MMC [5].

In order to take advantage of the full potential of a large-volume detector, it is therefore necessary to develop a method that allows separation of showers with exceptionally highly energetic muons from the dominant background of bundles containing low-energy muons of higher multiplicity. It has long been proposed to make use of the fact that the stochasticity of energy deposition along muon tracks increases with energy [4]. In this analysis, by identifying muon track segments with unusually strong photon

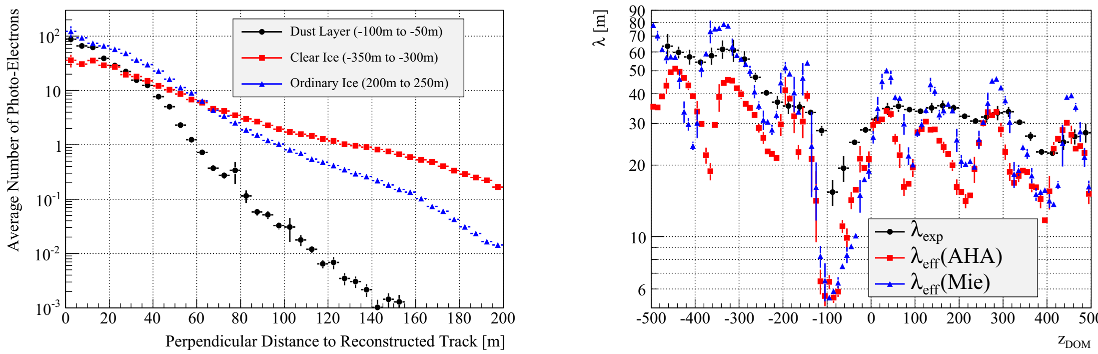

Figure 2: Left: Average number of photo-electrons registered in IceCube DOMs as a function of perpendicular distance from reconstructed muon tracks for three different depth bins. Values are averaged over events with a total charge $Q_{tot} >$ 1000 p.e. Right: Value of scattering parameter λ_{exp} from fitting distributions on the left to Eq. 1 in dependence of vertical depth. The value of $z_{DOM} = 0$ corresponds to the center of the IceCube array, located 1950 meters below the surface of the ice. The effective scattering length in two different ice models [6] is included for comparison. It is important to note that the physical meaning of λ_{eff} and λ_{exp} is not identical. Fine structures in the depth dependence are inherently smeared out in the experimentally derived parameter.

emission, the amplitude of individual stochastic losses can be used to infer the most likely energy of the parent muon, as illustrated in Figure 1.

2 Energy Estimation Method

The IceCube detector array records Cherenkov photons emitted by relativistic particles during passage through ice. The amount of charge in the optical modules provides calorimetric information that can be used to calculate the energy released in the event.

Previous energy reconstructions relied on prior assumptions about ice properties whose accuracy was necessarily limited. The method described here is based exclusively on experimental observations. Its is based on two simple assumptions:

- Down-going tracks in IceCube consist mainly of muon bundles dominated by minimum-ionizing muons which lose their energy smoothly and continuously.
- The total number of emitted Cherenkov photons is in good approximation proportional to the deposited energy.

As illustrated in Figure 2, the total amount of light registered in the DOMs can then be approximated by the empirical function

$$\frac{dE(x = x_0)}{dx} \propto Q(x_0) \cdot d(x_0) \cdot \exp\left(\frac{d(x_0) - 25}{\lambda_{exp}(x_0)}\right) \quad (1)$$

where $\frac{dE(x)}{dx}$ is the energy loss at vertical depth x, Q is the total charge in each DOM and d is the perpendicular distance between a DOM and the reconstructed muon track.

This data-derived model only relies on a single scattering parameter λ_{exp}, which varies in dependence of the local ice properties. From the charge in each DOM, it is possible to calculate a value that is approximately proportional to the energy deposited in its vicinity. Monte-Carlo simulated data are only required to determine the proportionality factor in Eq. 1 and for verification. Assuming point-like isotropic emitters on the track, clusters of exceptionally high values can be used to identify energetic stochastic energy losses. An example can be seen in Figure 3.

There are two important additional benefits that arise naturally from this technique. The first is the reduction of biases resulting from uncertainties about exact ice properties, allowing for detailed investigation of simulation biases. The other is the availability of information about differential energy deposition, permitting the construction of more accurate event energy estimators.

3 Analysis Procedure

This analysis was based on data from IceCube in its 59-string configuration (IC59). Only events with a total of more than one thousand photo-electrons registered in the detector were considered. This selection provides a sample of events at all zenith angles which is not biased by the quality criteria used to select physics filter streams.

The analysis procedure itself mainly consists of two relatively simple steps. First, a sample of muon tracks with strong stochastic losses inside the detector volume were identified. Then, the energy of the strongest single energy deposition was reconstructed and its spectrum compared to various benchmark models.

The principal conditions that were imposed in the selection are:

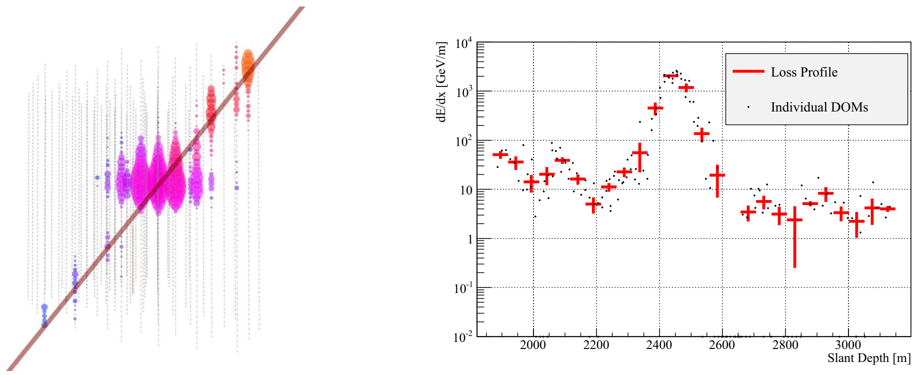

Figure 3: Example for massive stochastic loss event found in IC59 data. The energy deposition estimate shown on the right hand side is consistent with an 80 TeV cascade. The x-axis corresponds to the distance along the track, measured from the surface of the ice.

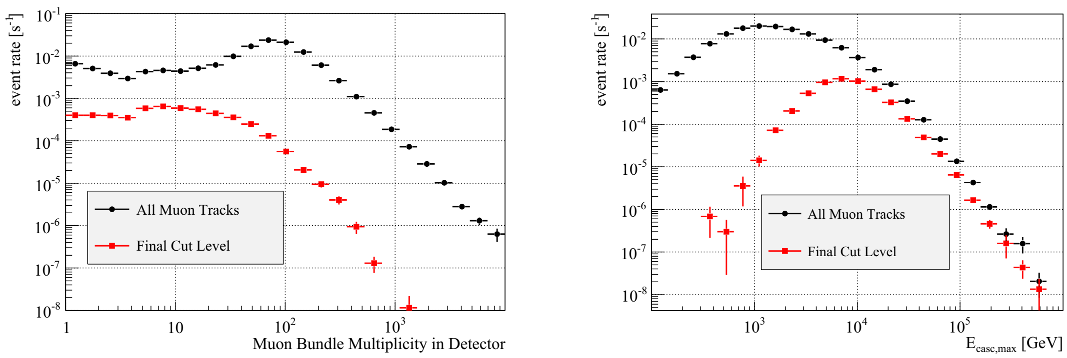

Figure 4: Left: Muon multiplicity in cosmic-ray showers at entry into detector volume before and after selection cuts, simulated using CORSIKA/SIBYLL. The analysis favors muon bundles of moderate multiplicities while reducing both high-multiplicity bundles and low-energy tracks with high recorded DOM charges due to unusual topologies. Right: Effect of selection cuts in dependence of true maximum stochastic loss energy. The effective threshold energy lies around 10 TeV.

- Presence of a well-reconstructed muon track with a length of at least 600 meters inside the detector volume.
- A peak energy loss value in a 50-meter bin along the track which exceeds the median differential energy loss in the event by a factor of 10.
- Location of peak energy loss within 150 meters from at least 50 DOMs, assuring containment within the main detector volume.

Figure 4 shows the cumulative effect of the cuts.

So far, the effective threshold energy for stochastic losses lies around 10 TeV. It is in principle possible to reduce this threshold further by relaxing the requirement on the total recorded DOM charge.

4 Result

To estimate the sensitivity of the method, the measured energy spectrum of stochastic losses was compared to simulations based on various primary composition models [7]:

- **Constant Composition**: The spectrum of each primary nucleus type changes by the same amount at an energy corresponding to the cosmic-ray knee.
- **Rigidity-Dependent Cutoff**: Each component of the cosmic ray flux is subject to a cutoff at an energy that is proportional to the charge of the nucleus.
- **Mass-Dependent Cutoff**: Similar to the previous model, but assuming a cutoff dependent on the nuclear mass. The main distinction here is a sharper transition, resulting in a stronger cutoff signature.
- **No Knee**: This additional model was included for purposes of illustration only, assuming unbroken spectra for each component and therefore completely

eliminating the knee. It should be noted that this assumption is strongly disfavored by previous experimental results.

Figure 5 shows the preliminary result, based on a subsample of 10 percent of the data taken with IC59. For models incorporating a cutoff in the individual primary spectra, a corresponding effect can clearly be discerned in the simulated muon-induced stochastic losses. The limited experimental statistics do not yet allow any definite statement about preferred models, even while neglecting systematic uncertainties.

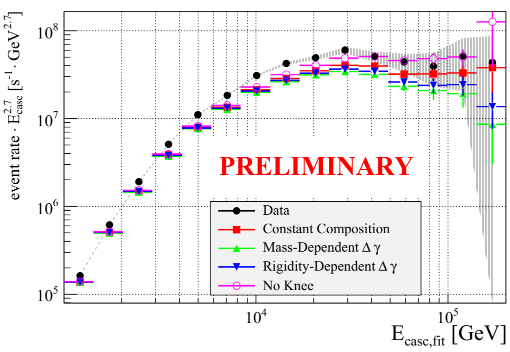

Figure 5: Comparison of reconstructed maximum stochastic loss energy for simulated and experimental data summed over all zenith angles. All simulated curves were obtained by reweighting the same data set generated with CORSIKA. Experimental data correspond to a subset of ten percent of IC59 events. The error band is purely statistical.

5 Conclusion and Outlook

As can be seen from comparing Figures 5 and 6, the highest muon energy found in the analyzed sample is most likely located around 500 TeV, with slight variations depending on the exact primary spectrum. This means that despite the fact that the spectrum falls off almost as the fourth power of the particle energy, the range of the measurement can be extended by roughly an order of magnitude compared to earlier experiments. The method presented here furthermore allows the measurement of cosmic-ray induced muon spectra independently of the zenith angle, introducing an entirely new degree of freedom.

Consequently, it will be possible to address a variety of new physics issues that were previously inaccessible. It has already been demonstrated that the behavior of cosmic rays around the knee can now be probed directly. A separate but equally important question is the contribution of prompt production processes to lepton fluxes at high energies. In optimistic models, the charm-induced component becomes dominant around 300 TeV at near-vertical angles [8] and would therefore be directly measurable. If on the other hand the prompt muon flux were low enough to be dominated by decays of unflavored light mesons [9], it should be possible to set a stringent limit that would strongly constrain the atmospheric neutrino background in searches for astrophysical sources.

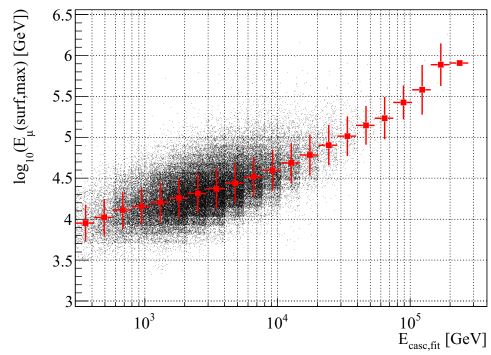

Figure 6: Relation between reconstructed cascade and muon surface energy obtained from Monte-Carlo simulation, assuming a poly-gonato primary spectrum and neglectic prompt muons. The change in slope around 10 TeV can be attributed to threshold effects.

It should also be emphasized that the method to distinguish unusually energetic muons from large-multiplicity background events is readily adaptable for analyses targeting neutrino fluxes at energies in the PeV range.

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