Measurements of the Air Shower Parameters with IceTop

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

Abstract: We study the lateral distribution function (LDF) of signals in the IceTop air shower detector as a function of distance from the air shower core. The completed IceTop detector consists of 81 stations with two tanks each. It can now study the signals at distances approaching 1 km from the core position. We discuss the general shape of lateral distributions of the signal and its dependence on the shower zenith angle and primary mass. We also show the simulated individual tank signal lateral distribution for a large number of simulated proton and iron showers. We find that the form of the lateral distribution function used for more widely spaced arrays of water Cherenkov detectors, Haverah Park and Auger in the EeV range, can also be used with appropriate parameters to describe IceTop data in the 10-100 PeV range.

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1 Introduction

IceTop, the surface air shower array above the IceCube neutrino detector, was completed in the 2010/2011 deployment season. IceTop consists of 81 stations, each of which has 2 tanks of area 2.7 m^2 containing 90 cm of clear ice. The average distance between the tanks in a station is 10 m and the average distance between stations is 125 m. The Cherenkov light generated by the charged particles that hit the tanks is collected by two digital optical modules (DOMs) that run at different gains to increase the dynamic range. The signal strength is measured in vertical equivalent muon units (VEM), i.e. the signal that a 1 GeV vertical muon produces in the tank. A station triggers when there are signals above the threshold (0.16 VEM) in both tanks within one microsecond. In this way we avoid triggering on coincidental muons that belong to different atmospheric cascades.

The current shower reconstruction of IceTop events is based on a procedure which was designed when the array contained only 26 stations in a much smaller area [1]; the reconstruction procedure is applied to showers that trigger at least five stations. The signal lateral distribution function in this procedure does not include tanks with zero signal (i.e. tanks that do not trigger) and the fitting routine accounts for these tanks with a separate, no-hit probability, term in the likelihood function.

In this paper we instead use a lateral distribution function of the form [2]

$$S(r) \,=\, A \times r^{-(\eta + r/r_0)}, \tag{1}$$

where $S(r)$ is the signal at a perpendicular distance r from the shower core in shower coordinates; η, r_0, and A are fit parameters. This form has been used for Haverah Park [3] and Auger [4] to fit showers observed with water Cherenkov tanks. IceTop is at a much higher altitude (2835 m) than HP (sea level) and significantly higher than Auger (1400 m) and collects data in a different primary energy range with detectors spaced by 125 m as compared to several hundred meters for HP and 1500 m for Auger. We investigate here the extent to which the lateral distribution form used for the other Cherenkov shower detectors scale to the location and energy range of IceTop. Everywhere in this paper, S(r) gives the signal strength at a perpendicular distance r from the shower core in shower coordinates. We include tanks with and without a signal directly in the lateral fit, both for simulated and observed air showers.

2 Monte Carlo Calculation

To study the lateral distribution we have simulated air showers initiated by protons and iron nuclei with fixed primary energies of 10 and 100 PeV and fixed zenith angles of 0, 25, and 45 degrees. Air showers are simulated with CORSIKA-SIBYLL [5] and the detector simulation uses Geant4 [6] for the tank response. 50 showers per primary

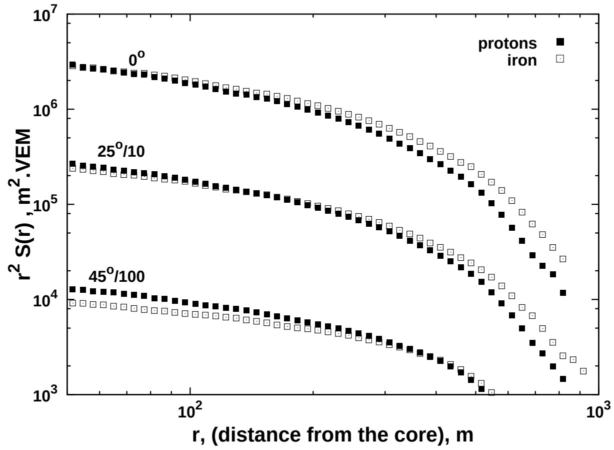

Figure 1: LDF of the signal strengths (weighted by square of the distance from core) for 100 PeV simulated proton and iron showers at three zenith angles.

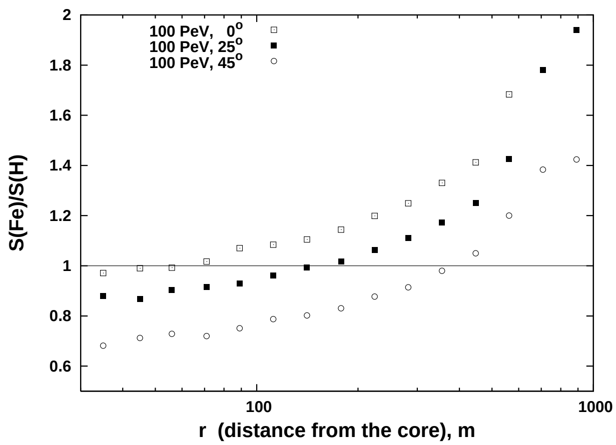

Figure 2: Ratio of the signal strength in simulated iron to proton showers for three zenith angles.

type, energy, and zenith angle were dropped on the IceTop array 100 times each within a 600 meter radius from the array center. As a result, there are 5,000 showers in each set. The simulated showers were reconstructed with the current standard procedure and all results presented below use the reconstructed shower core position, direction, and shower energy for event selection. Fewer than 200 showers in each set were not reconstructed well and are not analyzed here.

Figure 1 shows the average LDF of the IceTop signals for simulated proton and iron initiated showers at the three zenith angles. As expected, the proton showers have higher signals close to the shower core and iron showers have higher signal density at large distances from the core[1]. The intersection point of the proton and iron signals LDF changes with zenith angle and increases significantly even at the modest zenith angle of 45 degrees. The ratio of iron to proton signal LDF is presented in Figure 2. While for strictly vertical showers the intersection point is at about 50 m from the shower core; it is between 120 and 150 m

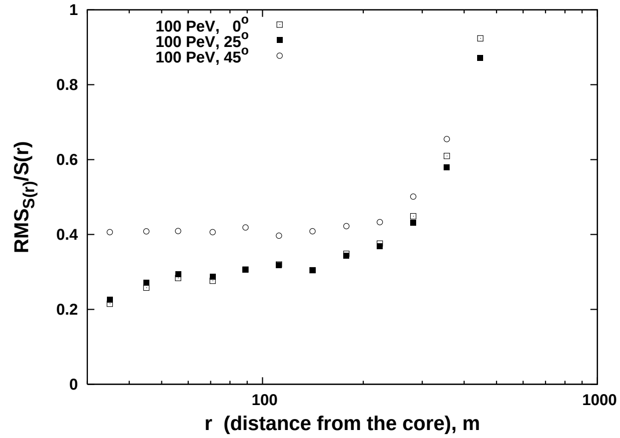

Figure 3: The ratio of RMS of the signal to its strength in simulated 100 PeV proton showers at three different zenith angles.

away from the core for θ=25 degrees and above 300 m at 45 degrees. Furthermore, although not shown here, the intersection point for 10 PeV showers is relatively larger for each angle; it is around 130, 180, and 400 m for θ=0, 25, and 45 degrees, respectively. The IceTop reconstruction procedure currently uses the signal at 125 m, S_{125}, from the shower core as the energy-related parameter, which seems to be mass independent for showers near the peak of the angular response for IceTop (25 degrees) as the classical papers of A.M. Hillas [7] recommend. However, as we see in Figure 2 for IceTop, there is no single distance from the shower core that is independent of mass for all energies and angles. Minimizing the fluctuations is also desirable in the choice of an optimum distance r used for energy assignment. Figure 3 shows the ratio of $\mathrm{RMS}_S/S(r)$ for E = 100 PeV proton showers and the three angles. The signal fluctuations are almost constant between 50 m and 150 m from the shower core for all three angles. The fluctuations are higher for the most inclined showers and still constant below 150 m distance from the core. the goal is to apply the lateral distribution function to experimental data which may include a mixture of proton, iron, and several other primaries. Therefore, it is instructive to look at the VEM range of signals for a given primary energy for both proton and iron together. As an example, we show in Fig. 4 the signals measured by IceTop in 100 proton and 100 simulated showers of primary iron nuclei. At distances around 100 m the signal variation is slightly larger than a factor of two. At much larger distances, around 500 m, the signal variation increases to more than one order of magnitude. A fraction of these fluctuations is due to the fact that we plot proton and iron induced showers together. There is a strong increase in fluctuations for each species at distances greater than 300 m, as shown in Fig. 3. Note also the relatively small statistics at distances below 100 m.

1. Everywhere in this paper, distance from the core is the perpendicular distance from the core in shower coordinates.

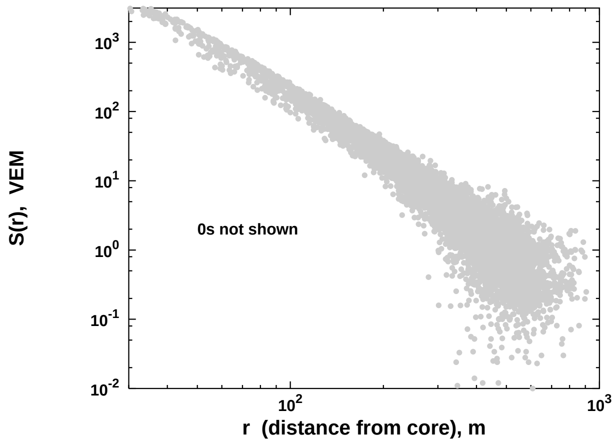

Figure 4: The signals recorded by all non-zero tanks for 100 proton and 100 iron induced vertical showers of energy 100 PeV are plotted as a function of the distance to shower core.

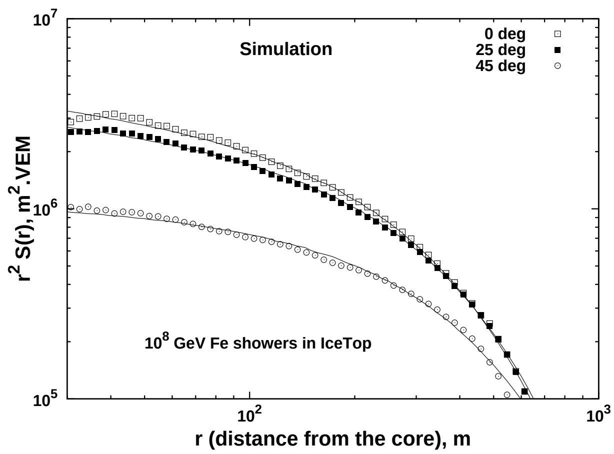

Figure 5: The average LDF of the signal strength for 100 PeV simulated iron showers at three zenith angles fitted with the HP-like function.

3 Fitting the simulated signal LDF

Both HP and Auger have fitted their data with a lateral distribution function similar to Eq. 1 r_0 fixed. Here we fit the average of the simulated showers at each energy with the same form. As an illustration, the signal LDF of the simulated 100 PeV iron showers and the fits obtained are shown in Fig. 5. As expected, the lateral distribution becomes flatter with angle. The parameter η is 2.22, 2.21, and 2.06 for 0, 25, and 45 degrees, respectively. The respective r_0 values are 1410, 1507 and 1783 m. The respective normalization parameter A is $7.18{\times}10^6$, $5.31{\times}10^6$, and $1.25{\times}10^6$ VEM. The χ^2 values of all fits are smaller than 1 per degree of freedom.

The fits of simulated proton showers have similar results. The η values are 2.25, 2.22, and 2.10 for 0, 25, and 45 degrees, respectively. The respective r_0 values are 1215, 1280 and 1474 m. While η values are similar for proton and iron showers, the r_0 values are always significantly smaller by about 200 m than those of iron showers. The respective normalization parameter A is 8.58×10^6 , 7.29×10^6, and 2.02×10^6 VEM for proton showers.

One has to note that the fits are not very good for core distances less than about 50 m. The reason is that we are using reconstructed position of the shower core. The average error in the core position is less than 20 m but this error still affects the LDF at small distances in a negative way. The statistics at small distances is also low. For these reasons the measured or interpolated signal strengths at small distances are not reliable.

4 Fitting of individual showers

The next step in the study of the signal lateral distribution function is the fitting of individual showers. We have attempted to fit individual simulated and experimentally detected showers with the function of Eq. 1. The fitting procedure is less stable when applied to individual showers especially because there are usually few points at distances smaller than 100 m from the shower core. This makes the r_0 parameter vary even more than in the case of average lateral distribution from a large number of showers.

The well fitted showers, however, show a good agreement between the experimentally detected and the simulated showers. To compare these two sets of showers we chose experimental showers with standard IceTop reconstructed parameters very close to the simulated (fixed primary energy E_p and zenith angle θ) ones. For vertical showers, for example, we chose showers with $\cos(\theta) \geq 0.95$ and with $1.97 \leq \log_{10}(E_p/\mathrm{PeV}) \leq 2.03$. Figure 6 shows the LDF fit of a simulated proton (top) and an experimentally detected shower (bottom). Both showers have a large number of triggering stations - 48 stations in the simulated shower and 46 in the experimental one. The experimental shower shown in Fig. 6 is from 2010 when IceTop consisted of 73 stations (or 146 tanks). The tanks with '0' signal are not shown, but they are included in the average for each annular bin of r. In the graph of the experimental shower we also show the average signal strength calculated in logarithmic radial bins around the reconstructed shower core.

The fits have a χ^2 of 0.6 p.d.f. However, the performance of the fit will depend on χ^2 distributions from fits on a reasonable sample of showers; a detailed study is needed in this regard.

5 Summary

We have studied the lateral distribution of air shower signals in IceTop tanks using a function similar to the one used by Haverah Park and Auger Observatory. Tanks with signals below threshold are included as zeros in averaging the signal in each radial bin. The simulated proton and iron showers at 10 and 100 PeV can be described with lateral

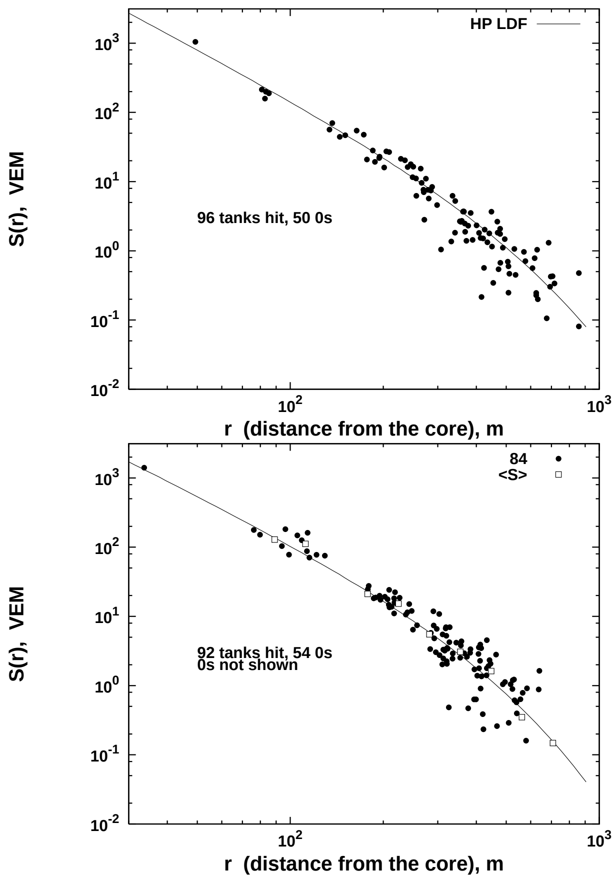

Figure 6: Example fits on two individual showers; both showers are almost vertical ($\cos(\theta)\geq 0.95$) with energies close to 100 PeV. Top: a simulated proton shower. Bottom: experimentally observed shower.

distribution functions of the VEM signal having the same form as those used by the Haverah Park and Auger Observatory. We have not studied the lateral distribution of signal at distances smaller than 50 m because the lateral distance and the uncertainty in the reconstructed core position become comparable to each other; this results in a large uncertainy in the signal at shorter distances. The LDF of both iron and proton showers becomes flatter with increasing zenith angle.

We also see, as expected, the flatter lateral distribution of the simulated iron showers compared to that of the proton showers. The highest ratio of the iron to proton LDF occurs at distances more than 500 m from the shower core. We also show the distance at which the relative signal strengths of the signals from proton and iron showers are equal. the crossover radius depends significantly on the shower zenith angle and also on energy. For 100 PeV showers, it varies between 50-150 m for zenith angles as large as 25 degrees, and it is above 300 m at 45 degrees. For 10 PeV showers, not shown here, it varies between 130-180 m for zenith angles as large as 25 degrees, and it is above 400 m at 45 degrees. For a mass independent energy reconstruction in this energy range, we will explore the possibility of scaling the energy estimation reference distance, with the energy and zenith angle of the shower using an iterative procedure. In this regard, it is encouraging that, for showers in the peak of the angular distribution for IceTop ($\theta \sim$25 degrees) and energies 10-100 PeV, the variation of the iron to proton signal ratio is around 1 and it has about 10% variation for the reference distance range of 100-150 m. It is also encouraging that the signal fluctuations are almost constant in the distance range 50-150 m.

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