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Lateral Distribution of Air Shower Signals and Initial Energy Spectrum above 1 PeV from IceTop

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Abstract: The IceTop surface detector array is part of the IceCube Neutrino Observatory that is presently being built at the South Pole. In a triangular grid with a spacing of $125\,\mathrm{m}$, up to 80 pairs of ice Cherenkov tanks will be set up, 16 of which were already in operation in 2006. The data from this array allows the reconstruction of a first preliminary energy spectrum in the range of about $1\,\mathrm{PeV}$ to $100\,\mathrm{PeV}$. To reconstruct the primary energy of a cosmic ray particle, a fit to the lateral distribution of the air shower signals has to be performed. We have developed a functional description of expected lateral distributions and of the corresponding fluctuations of the measured signals. The function and its parameters have been tuned in a CORSIKA simulation study with parametrised particle responses. From a detailed detector simulation, the fluctuations could be extracted and qualitatively compared with experimental data. Some performance tests and an initial energy spectrum, uncorrected for efficiency near threshold, are presented.

Introduction

When a high energy cosmic ray hits the earth's atmosphere, it induces an extensive air shower (EAS) whose axis and energy can be reconstructed by detector arrays at ground level. In general, the arrival times of the particles deliver the direction information while the signal strength distribution is used to reconstruct the core and size of the shower. The shower size is usually represented by the signal S_R at a certain perpendicular distance R from the shower axis ("core radius"). With the spacing of IceTop, S_{100} at $R = 100\,\mathrm{m}$ proved to be a stable and reliable quantity in the fit procedure.

The signal S of an IceTop tank is derived from the charge of two photomultipliers that are operated at different gains ($5 \cdot 10^4$ and $5 \cdot 10^6$ in 2006) to enhance the dynamic range of the detector well above 10^5. They collect the Cherenkov photons produced by the shower particles in the $2.45\,\mathrm{m}^3$ of ice in each tank. The total signal is proportional to the deposited energy in the tank since the Cherenkov light and the deposited energy are both approximately proportional to the track lengths of the charged particles. Using atmospheric muons for calibration, the signals can thus be converted to the detector-independent unit VEM (vertical equivalent muon), which is equivalent to about $200\,\mathrm{MeV}$ of deposited energy [1].

To estimate the energy of the primary particle and determine the shower core, a log-likelihood fit is applied to the measured signals. This requires a lateral distribution function (LDF) $S(r)$ at a given core radius, and a parametrisation of the signal fluctuations. The likelihood also includes a term for stations without trigger.

LDF and Fluctuation Parametrisation

To find an appropriate LDF for IceTop, lateral distributions of CORSIKA shower simulations [2] were analysed. The hadronic interaction mod-

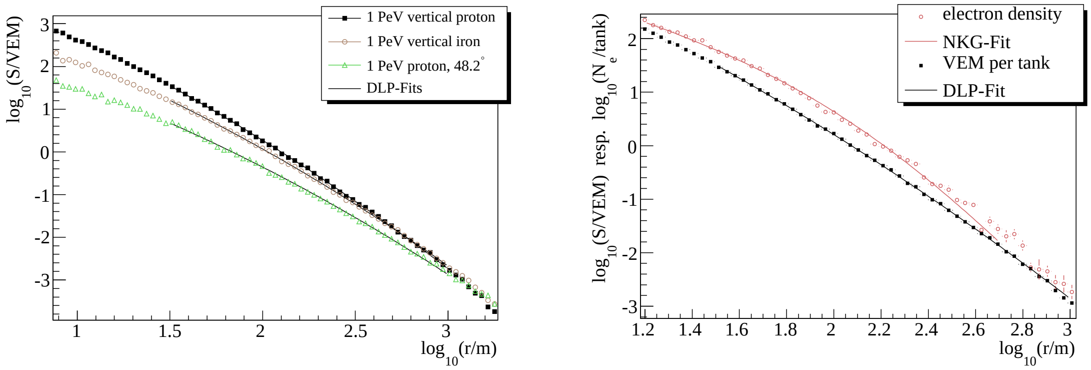

Figure 1: Left: Derived lateral signal distributions of IceTop tanks for three different simulated showers, fitted with the DLP function described in the text. Right: Comparison between lateral electron density and tank signal distribution, fitted with NKG and DLP respectively.

els used in all simulations are Sibyll 2.1 [3] for energies above $80\,\mathrm{GeV}$ and Fluka [4] below that. Each shower particle was weighted with an average response function $S_j(E)$ derived from single particle simulations that were carried out with a Geant4-based detector simulation [5]. The particle types considered are $j = \{\gamma, e^{\pm}, \mu^{\pm}, p, \bar{p}, n, \bar{n}, \pi^{\pm}, K^{\pm,0}\}$, which are the most abundant in air showers. Three examples of the distributions that were found, and a comparison to the electron density distribution described by the NKG function [6] are given in Fig. 1. It is remarkable that the main feature of the NKG function in double logarithmic representation, which is a bend with a maximal curvature approximately at the Molière Radius ($128\,\mathrm{m}$ at the South Pole [7]), cannot be seen in the tank signal lateral distributions. This is presumably a consequence of the fact that the energy deposition is not proportional to the particle number.

The function found to fit these distributions well in a range between 30 and $1000\,\mathrm{m}$ is a parabola in a double logarithmic representation (DLP), which can be written as

$$S(R) = S_{R_0} \left(\frac{R}{R_0}\right)^{-\beta-\kappa\,\log_{10}\left(\frac{R}{R_0}\right)} \qquad (1)$$

with $R_0 = 100\,\mathrm{m}$ being the reference core radius, β the slope at R_0, and $\kappa \approx 0.303$ the curvature of the parabola. This curvature is approximately a constant for all hadronic showers and thus a fixed parameter for all fits on real data. The parameter β is roughly linearly connected to the shower age parameter of the NKG function via $s_{NKG} = -0.94\,\beta + 3.4$ for all simulated angles, energies and nuclei.

To study the fluctuations σ_S of the approximately log-normally distributed tank signals, two analyses were done. Figure 2 shows the comparison of the dependencies of σ_S on S that were found. The points designated with "tank-to-tank" indicate the outcome of a study of signal differences between the two tanks separated by $10\,\mathrm{m}$ at each detector station. Shower fluctuations were thus measured directly in data and the result is compared to simulated data that was produced with CORSIKA showers processed with a Geant4 detector simulation of the array. The lower points are taken from a similar simulation with tanks set up in a ring-like structure. Since the former is biased by uncertainties in reconstruction and shower intrinsic correlations, and the latter depends on the quality of the detector simulation, the two methods are not fully comparable but should yield results in the same order of magnitude. This could roughly be verified, although the tank-to-tank fluctuations have some features at higher amplitudes that are most likely an artefact from misreconstructed cores that are very close to one of the tanks. In the full array simulations described below, the parametrisa-

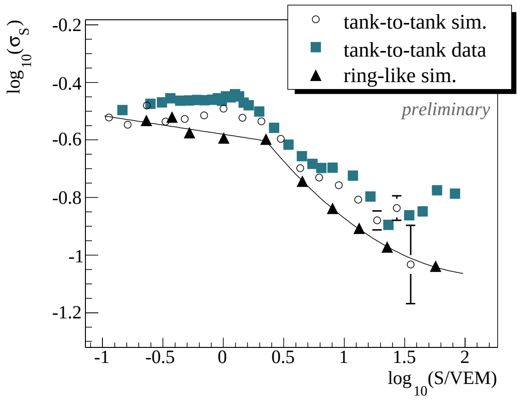

Figure 2: Dependency of the signal fluctuation σ_S on the signal S in data and different simulations (the error bars are partly smaller than the markers). σ_S designates the standard deviation of $\log_{10}(S)$. The differences between the methods are discussed in the text. The solid line indicates the parametrisation that was extracted for the lateral fit.

tion taken from the ring-like simulation delivers a better core and energy resolution and is therefore used in the fit. The dependence of σ_S on the core radius was found to be in the order of $15\,\%$ for radii above $30\,\mathrm{m}$ and is therefore negligible.

With the parametrised CORSIKA simulations described above, it was found that for zenith angles $\theta < 50°$, the dependence of S_R on $x = \sec\theta$ can be described by parabolas (Fig. 3). Assuming that the maximum of $\log_{10} S_R$ and its position x_{max} linearly depend on $\log_{10} E$, a function $S_R(\theta, E)$ was found that fits all data points and can be inverted analytically to $E(S_R, \theta)$. For several R between 50 and $1000\,\mathrm{m}$, the parameters of $E(S_R, \theta)$ were interpolated such that the conversion from S_R to the primary energy can be done at any radius R_{opt} that might be regarded optimal for physical or numerical reasons. Presently, to be as independent as possible from the quality of the LDF, R_{opt} is chosen event by event in a way that $\log_{10} R_{opt}$ is the mean logarithmic core radius of all tanks that were actually used in the fit.

This energy conversion does not yet take into account the influence of the primary mass. From the shower size differences observed between proton and iron showers in the simulations ($\Delta \log_{10} S_R \approx 0.1$), the systematic uncertainty on the spectral index of the following spectrum can be estimated to be $\sigma_\gamma \approx 0.1$.

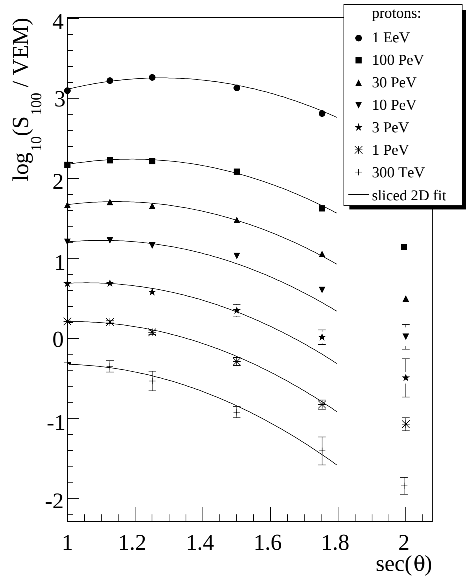

Figure 3: CORSIKA simulations of $\log_{10}(S_{100})$ as a function of $\sec\theta$ for various energies. The lines are projections of the fit that was performed on all data points simultaneously ($\chi^2/\mathrm{ndf} = 41.2/32$).

Performance and Results

To benchmark the performance of the LDF, CORSIKA simulations of $1\,\mathrm{PeV}$ vertical showers were carried out on the 2006 array configuration, using the tank intersects of the shower particles and the above $S_j(E)$ tank response parametrisations to scale the responses of the particles. The simulation also includes the generation of PMT responses, digitisation and the behaviour of the IceCube trigger devices. Thus the simulated raw data completely resembles the level and format of experimental raw data. The quantities that serve to estimate the quality of the LDF are the core position resolution σ_{core}, the energy resolution $\sigma_{\log_{10} E}$, the

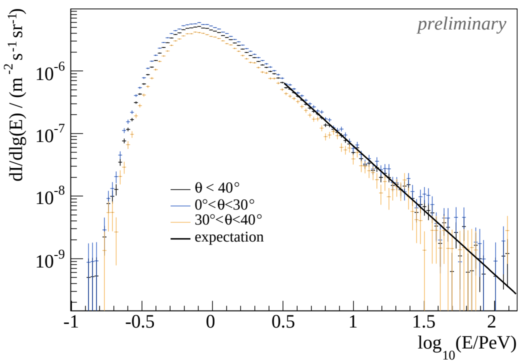

Figure 4: Preliminary, raw energy spectrum without acceptance correction. The difference between high and low zenith range indicates the systematic uncertainty. Though not deconvoluted yet, the high-energetic part is compared to the expected spectrum and agrees well with it (solid line, [8]).

reconstruction efficiency ϵ and the mean of the χ^2 distribution.

Compared to a simple power law and the NKG function, the numbers found indicate a slight preference for the DLP function, especially concerning the reconstruction efficiency. For vertical $1\,\mathrm{PeV}$ showers, the core and energy resolution are $\sigma_{core} = 12.8\,\mathrm{m}$ and $\sigma_{\log_{10} E} = 0.094$. However, once a bigger array is available in the coming years, this has to be reevaluated.

With the energy extracted as described above, a dataset with an effective lifetime of $0.692 \cdot 10^6\,\mathrm{s}$ was analysed. Requiring 5 triggered stations, the reconstructed core to be $50\,\mathrm{m}$ inside the array and the zenith angle to be $\theta < 40°$, an exposure of $0.67 \cdot 10^{11}\,\mathrm{m}^2\mathrm{sr\,s}$ is achieved. In this dataset, 192507 shower events were detected. From the known energy spectrum [8] of charged cosmic rays, one can estimate an effective reconstruction threshold of $\sim 500\,\mathrm{TeV}$ and expect approximately 1000 events above $10\,\mathrm{PeV}$ and 10 events above $100\,\mathrm{PeV}$. In the dataset, 800 and 5 events were found respectively.

The raw distribution of energy estimates without acceptance correction is shown in Fig. 4. The high energy part, where the efficiency can be assumed to be constant and close to 1, the slope of the spectrum agrees well with the slope of $\gamma \approx 3.05$ that is expected from other experiments, drawn as a solid line for comparison. The absolute scale of the raw spectrum is lower than the expectation, which indicates the need for more simulations to tune the energy extraction and correct for efficiencies.

Conclusion

With the 2006 array configuration, we will be able to measure the cosmic ray energy spectrum from 0.5 to $100\,\mathrm{PeV}$. The signal distributions are well understood, and applying advanced log-likelihood fits we are able to reconstruct the cores and sizes of the measured showers with good precision. Since February 2007, already 26 stations are in operation, which covers a third of the total planned area. This and the development of an unfolding procedure will enable IceTop to measure an energy spectrum well above $100\,\mathrm{PeV}$ at the end of 2007.

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