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Alternative energy estimation from the shower lateral distribution function

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The surface detector technique has been successfully used to detect cosmic ray showers for several decades. Scintillators or Cerenkov water tanks can be used to measure the number of particles and/or the energy density at a given depth in the atmosphere and reconstruct the primary particle properties. It has been shown that the experiment configuration and the resolution in reconstructing the core position determine a distance to the shower axis at which the lateral distribution function (LDF) of particles shows the least variation with respect to different primary particles type, simulation models and specific shapes of the LDF. Therefore, the signal at this distance (600 m for Haverah Park and 1000 m for Auger Observatory) has shown to be a good estimator of the shower energy. Revisiting the above technique, we show that a range of distances to the shower axis, instead of one single point, can be used as estimator of the shower energy. A comparison is done for the Auger Observatory configuration and the new estimator proposed here is shown to be a good and robust alternative to the standard single point procedure.

1. Introduction

Surface array detectors have been used to detect cosmic ray showers due to a large number of properties, including their stability, large detection areas and duty cycle. Nowadays, the arrival time of the particles in the shower can be measured with a good resolution (tenths of ns) leading to an excellent reconstruction of the primary particle direction ($> 1°$) and therefore good precision in anisotropy studies. Besides that, ground array detectors have a well defined aperture resulting in a straight forward determination of the cosmic ray spectrum.

However, since ground array experiments detect a sample of the shower development at a single fixed depth, the energy reconstruction can not be derived in a direct or calorimetric way. In fact, the most important information from which the parameters of the primary particle should be reconstructed is the lateral distribution of particles in the shower. In 1969, Hillas et al. [1] showed that at a given distance of the shower axis, the fluctuations of the lateral distribution function (LDF) due to intrinsic shower fluctuations are minimized. In subsequent works [2], it was also shown that the measured signal fluctuation is very small at a certain distance in despite of the type of primary particles, Monte Carlo simulation models and specific LDF functions.

The distance at which the fluctuations reach their minimum is a convolution of the intrinsic shower-to-shower fluctuation, the experimental uncertainties and the reconstruction procedures. One very important experimental input is the array spacing which mathematically determines the properties of the LDF fit [3]. The Haverah Park experiment [4] used water Cerenkov tanks and determined the distance of least fluctuation to be 600 meters. Operating with the same ground array technique, the Pierre Auger Observatory [5] has determined the distance of least fluctuation to be 1000 meters.

The scope of this work is to explore the possibility to use the integral of the LDF within a given interval as an energy estimator. A similar procedure is used by the KASCADE Collaboration [6] in order to reconstruct the energy of the primary particle. We investigate the fluctuation and the resolution of this parameter based on simulation studies for showers with energies from 10^{18} to $10^{19.5}$ eV.

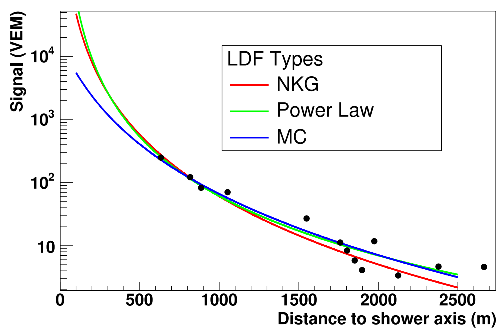

Figure 1. Example of a simulated event with energy $10^{19.5}$ eV and zenith angle 45° and three fitted lateral functions.

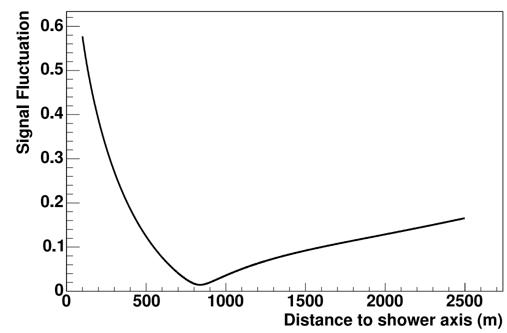

Figure 2. Fluctuations of the signal as a function of the distance to the shower axis. There is one clear minimum in the fluctuations around 800 m.

2. Simulation and Reconstruction

We have used a simplified numerical simulation of the signal in a water Cerenkov tank given by a parametrization of the lateral distribution of the particles as a function of the primary energy as explained in reference [3]. Poissonian noise is considered. We simulated a 1500 stations array with 1.5 km spacing. Only stations with signal above 3.2 VEM which did not saturate were considered in our analysis.

The signal and position of each station was used to fit three different LDF types as given below:

NKG-Type:

$$S(r) = S(1000)\left(\frac{r}{1000}\right)^{-\beta-0.2}\left(\frac{r+r_s}{1000+r_s}\right)^{-\beta} \tag{1}$$

Power Law (PL):

$$S(r) = S(1000)\left(\frac{r}{1000}\right)^{-\nu} \tag{2}$$

Monte Carlo inspired (MC):

$$S(r) = 10^{A+Bx+Cx^2} \tag{3}$$

where $\nu = 5.1 - 1.4 \times \sec\theta$, $\beta = 3.3 - 0.9 \times \sec\theta$, $r_s = 700m$ and $x = \log(r/1000)$.

These functions where suggested by the Auger Collaboration in reference [7]. Figure 1 illustrates the procedure, black dots correspond to the simulated signal in the stations which were used to fit the three lines corresponding to each LDF type. Figure 2 shows the corresponding fluctuation where one clear minimum around 800 m can be seen.

It is also noticeable that the fluctuation is below 10% for a large interval of distances to the shower axis ($\sim$

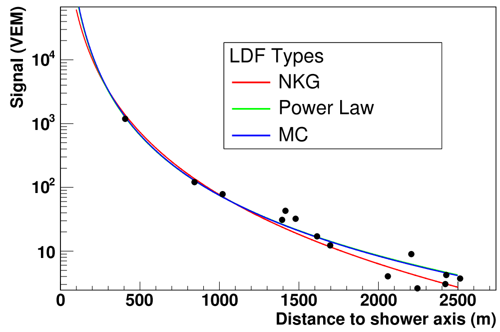

Figure 3. Example of a simulated event with energy $10^{19.5}$ eV and zenith angle 45° and three fitted lateral functions.

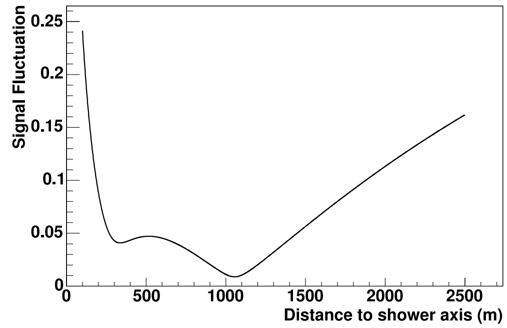

Figure 4. Fluctuations of the signal as a function of the distance to the shower axis. Note the two minima in the fluctuation.

from 500 to 1400 m). Figures 3 and 4 show another example of LDF fit and the corresponding fluctuation. In this case, the fluctuations have two clear minima and an even larger interval of distances ($\sim$ from 200 to 1500 m) with fluctuations below 10% is seen.

Following this procedure we simulated 100 proton showers corresponding to each primary energy of $10^{18.5}$, $10^{19.0}$ and $10^{19.5}$ eV, zenith angle of 45° and calculated for each event the distance of minimum fluctuation (R_{opt}).

3. Results

Figure 5 shows the distribution of R_{opt} for all energies. If the fluctuations as a function of distance showed two minima, only the absolute minimum was included in the distribution shown in figure 5. We have only included showers for which we manage to fit all three functions and events which had no saturated tanks.

The use of one single point calculated to each event is under study. However, the discussion in section 2 and figure 5 suggest that the interval from $\bar{R}_{opt} - \sigma$ to $\bar{R}_{opt} + \sigma$ could be used as an energy estimator because the signal fluctuations are very small along this entire range.

We have also studied the distributions of R_{opt} for each energy $10^{18.5}$, $10^{19.0}$ and $10^{19.5}$ eV and we have verified the increase of $\bar{R}_{opt}$, from 895 m, to 913 m and 1040 m, respectively. Indeed figure 5 shows two peaks, the first corresponding to the distribution of showers with energies $10^{18.5}$ and $10^{19.0}$ eV and the second corresponding to showers with energy $10^{19.5}$ eV.

Figure 6 shows the value of the integral of the three LDFs from 790 to 1110 m for the energies considered in this analysis. The distributions of the signal at 1000 m (S(1000)) away from the shower axis were also studied. Table 1 shows the comparison of the spread of the distribution of the integral and the S(1000).

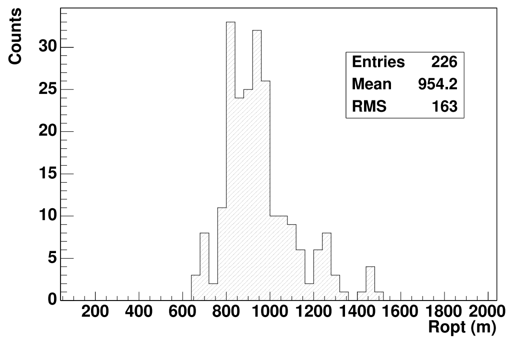

Figure 5. Distribution of distance where the minimum fluctuations occur.

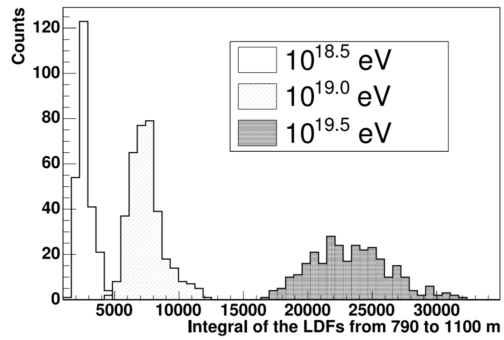

Figure 6. Distribution of the integral of the LDFs from 790 to 1100 m.

Table 1. Mean, RMS and Spread (RMS over Mean) as a function of energy for the S(1000) and integral distributions.

	$10^{18.5}$ eV		$10^{19.0}$ eV		$10^{19.5}$ eV	
	Int	S(1000)	Int	S(1000)	Int	S(1000)
Mean	8336	7.30	23470	19.53	73670	60.94
RMS	1891	1.57	4540	3.47	9945	7.66
Spread	22%	21%	19%	17%	13%	12%

4. Conclusion

Table 1 shows that the integral has a similar spread as that of the S(1000) values. A more detailed work regarding hadronic interaction models, several zenith angles and different primary particles is in preparation and the integral procedure has shown to be a promising good energy estimator.

5. Acknowledgments

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