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A measurement of the average longitudinal development profile of cosmic ray air showers between 10^{17} eV and 10^{18} eV

Z. Cao, for the HiRes/MIA Collaboration

High Energy Astrophysics Institute, Dept. of Physics, University of Utah

Abstract. The average extensive air shower longitudinal development profile is measured. Events between 10^{17} and 10^{18}eV recorded by the HiRes/MIA hybrid experiment are used for the average profile. Several functional forms are examined using this average profile. The best-fit parameters for the above functions are determined.

1 Introduction

The atmospheric nitrogen fluorescence light technique plays an increasingly important role in extremely high energy cosmic ray observations. The success of the Fly's Eye and HiRes (T.Abu-Zayyad *et al.* , 2000) experiments encourages the employment of this technique in future projects like the Auger experiment (A. Etchegoyen, *et al.* , 1996), the Telescope Array proposal (The TA collaboration , 2000) and space based experiments like EUSO (L. Scarsl *et al.* , 2000) and OWL (O. Catalano , 1999). By using this technique, the air shower longitudinal development can be reconstructed by assuming a functional form of the features of the shower development. The shower maximum position can be determined directly and shower energy can be measured by integrating this shower profile. In practice, empirical functions based on data at lower energies or based on theoretical electromagnetic cascade calculation are used at the highest energies, e.g. above 10^{17}eV. However, none of these has been experimentally tested at these energies in the atmosphere. The HiRes prototype detector provides a angular degree by degree measurement of the intensity of the fluorescence light produced by the shower electrons along the shower axis. This light intensity, after corrections, is proportional to the shower development profile. With the help of the shower muon arrival time information from the MIA experiment (A. Borione *et al.* , 1994), the shower geometry is well determined. This offers an ideal condition for measurement of the average shower longitudinal development.

Correspondence to: Z. Cao(caozh@cosmic.utah.edu)

2 Observation and preparation of data

During the lifetime of the HiRes/MIA hybrid experiment between Aug. 23, 1993 and May. 24, 1996 the total effective coincident exposure time was 1532 hours. A total of 2881 coincident events were recorded. 488 events survive the criteria for "good" events. These have a clear profile shape and minimum Cerenkov light component in the angular bin signals, e.g. the Cerenkov light fraction is less than 15% on average.

Since only the fluorescence light component is proportional to the corresponding number of shower charged particles, the Cerenkov light component should be subtracted from the bin signals.The contribution to the bin signal from scattered light from the accumulated Cerenkov beam along the shower axis is estimated as follows: we assume that the Cerenkov light beam in the angular bin is due to shower electrons in the previous adjacent angular bin. After taking into account the attenuation of the Cerenkov light beam traveling through the air between the bins, the contribution of scattered Cerenkov light from the beam into the detector is estimated based on the Rayleigh scattering theory and Mie scattering by aerosol. To complete this procedure, in the first observed bin the Cerenkov light is assumed to be *zero*. The effect of the Cerenkov light subtraction is shown in Fig 1, where the average shower transition curves before and after the subtraction are given in the same plot.

To take the average over the showers with different energies and positions of shower maxima, we align all showers in atmospheric depth and normalize them by their own maximum size, N_m. This is done by rewriting the bin signal as $n(s) = N(s)/N_m$, here the shower "age" parameter, i.e. $s = \frac{3X}{X+2X_m}$, instead of depth, X is used.

3 Tests of trial functions

The measured average profile is fitted with several well known trial functions such as the Gaisser-Hillas (T. Gaisser , 1977),

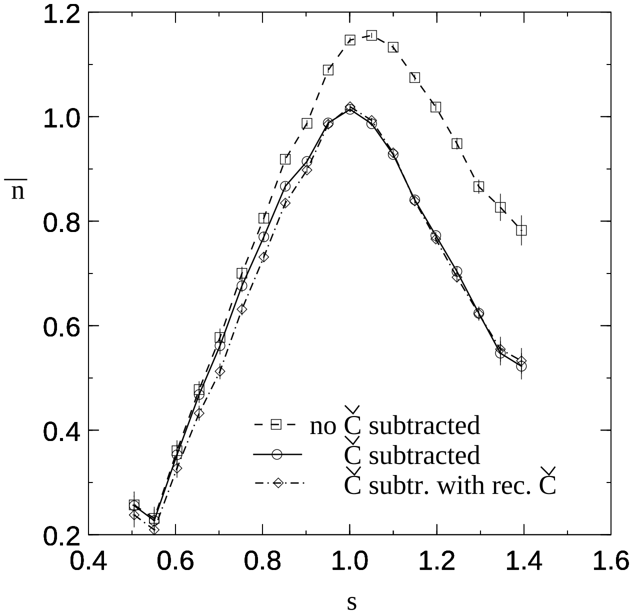

Fig. 1. The average shower transition curve. Solid line plus circles refers to the bin signal based recurrent Cerenkov-light-subtracting method, the dashed line plus squares is the raw signal including the Cerenkov light. The dash-dotted line plus diamonds corresponds to a different Cerenkov light subtraction method.

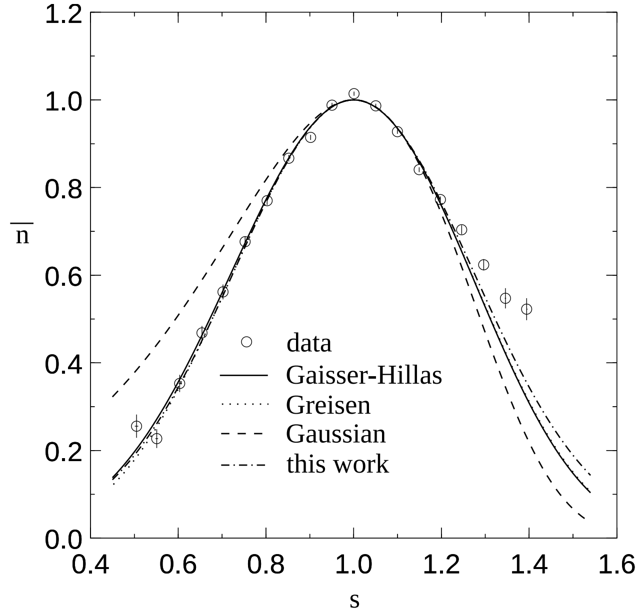

Fig. 2. Comparison between the data and test functions. Circles refer to data. The solid line refers to the G-H function, the dotted line to the Greisen function, the dashed line to the Gaussian function and the dash-dotted line to the newly proposed symmetrical Gaussian function of the shower age.

Greisen (K. Greisen , 1960) and a Gaussian forms. In terms of n versus s, they are

$$n(s) = \left(1 - \frac{1-s}{3-s}\frac{3T_m}{T_m - T_0}\right)^{T_m - T_0} e^{3T_m \frac{1-s}{3-s}} \ , \ \text{(G-H)} \quad (1)$$

$$n(s) = exp\left\{\frac{ys(2-3lns)}{3-s} - y\right\} , \qquad \text{(Greisen)} \quad (2)$$

and

$$n(s) = exp\left\{-\frac{(s-1)^2}{2\sigma^2}\right\} . \qquad \text{(Gauss.)} \quad (3)$$

where T_m and T_0 are two free parameters for the G-H form, y and σ are the single parameter for the Greisen and Gaussian form, respectively. Fig 2 shows the comparison between all the function forms and the measured average profile. All the three functions fit the data quite well. However, the dashed line is ruled out. It is a symmetric Gaussian function in depth X, i.e. $N(X) \sim exp\left\{-\frac{(X-X_m)^2}{2\sigma_X^2}\right\}$, which was used in Fly's Eye experiment for shower reconstruction. For the three successful functional forms, Fig 3 shows the details of the fits and corresponding χ^2 for each fit. Within the covered range of age, the data is not sufficient to distinguish between them.

We also notice that none of the functional forms is a good fit at both small and large ages. The reliable age range of data is from 0.6 to 1.3.

4 Systematic error analysis

In order to investigate the reasons for deviation from the test functions at both early and late stages of shower development, we apply the above analysis to Monte Carlo simulated events. The deviation turns out mainly due to the detector acceptance correction associated with those tubes which lie far from the shower-detector-plane.

We know that there is an uncertainty in the determination of the shower-detector plane direction of about 0.7 degrees (T. Abu-Zayyad *et al.* , 2001). This uncertainty causes a systematic overcorrection in the signals for off plane tubes. This becomes worse for a tube located far from the center of the phototube cluster.

Another source of the systematic error is setting the Cerenkov light to be zero in the first observed angular bin in the Cerenkov light subtraction scheme. It is found that the Cerenkov light is systematically underestimated by 7.7% because of this.

5 Conclusion

In summary, the shape of the extensive air shower longitudinal development is investigated in the energy range from 10^{17} to 10^{18}eV with the HiRes/MIA hybrid experiment. The profile is quite symmetrical as a function of the age of the shower. The "new Gaussian function" (3), the Greisen function (2) and the Gaisser-Hillas function (1) describe the shower shape almost equally well, with the χ^2's of 1.79, 1.87 and 1.93 respectively. This is the first direct measurement of the shower average longitudinal development profile at these en-

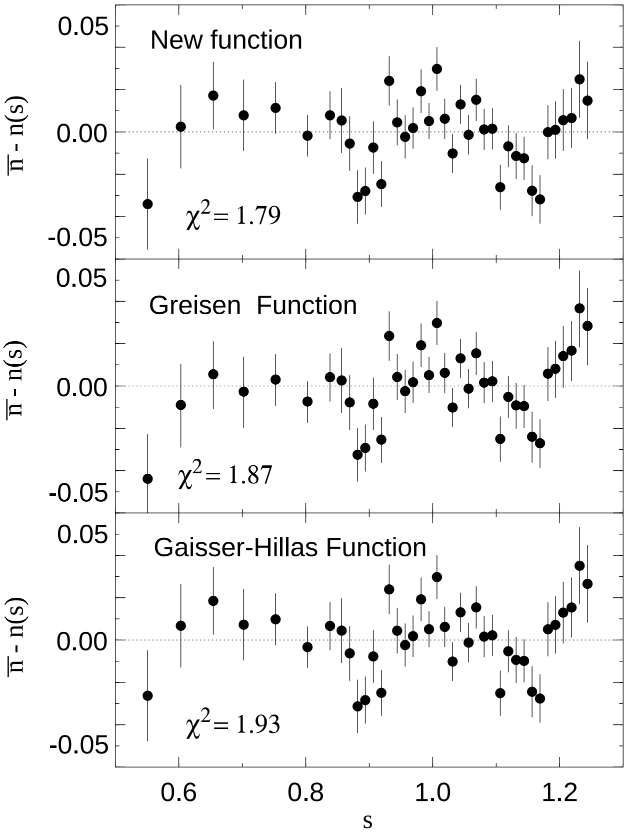

Fig. 3. Deviation of the data from the fits. The χ^2 is per degree of freedom. The "new function" refers to the Gaussian function in age, s, as shown in eqn (3).

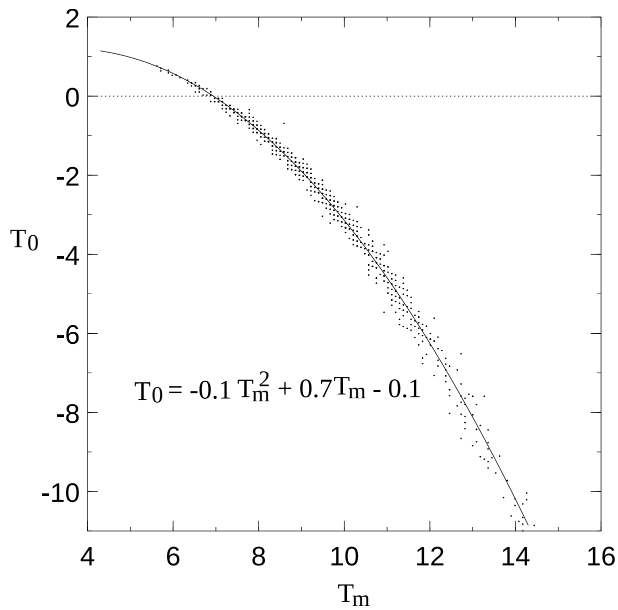

Fig. 4. The correlation between the parameter T_m and T_0 in G-H function

ergies and covering such a wide range of shower age. It is also noticed that the two parameters in Gaisser-Hillas function, i.e. T_m and T_0 are strongly correlated, as shown in Fig 4. A single parameter seems to be sufficient to describe such a symmetric function.

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