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Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
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A Measurement of the Average Longitudinal Development Profile of Cosmic Ray Air Showers from $10^{17.5}$eV to 10^{20}eV by HiRes-II

G. HUGHES FOR THE HIGH RESOLUTION FLY'S EYE COLLABORATION
Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854, USA
gahughes@physics.rutgers.edu

Abstract: A method to calculate the Average Longitudinal Shower profile has been applied to the High Resolution Fly's Eye Detector (HiRes) data. A complete detector simulation was used to throw CORSIKA (QGSJET) showers which are then analyzed using the same technique. The main features of the average showers are compared to the Monte Carlo as a function of energy. Systematic errors in the reconstruction of the profile are considered.

Introduction

Ultra High Energy Cosmic Rays (UHECRs) are many times more energetic than particles accelerated in colliders. The Extended Air Shower (EAS), discovered by Pierre Auger, resulting from their interaction with the atmosphere give us the opportunity to study not only Cosmic Rays (CRs) but also these extremely energetic cascades.

Detection of atmospheric nitrogen fluorescence [1] has long enabled experiments to observe and reconstruct air showers. This approach has been employed successfully, in the Fly's Eye experiment, then HiRes and Telescope Array [2, 3, 4].

Shower shapes have been predicted though theoretical calculations and by studying data, as in the method of constant intensity cuts [5]. Equation 1 shows the Gaisser-Hillas (GH) parametrization.

$$N(X) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{(X_{max}-X_0)}{\lambda}} \times e^{\frac{(X_{max}-X)}{\lambda}} \quad (1)$$

N(X) describes the number of particles in the shower at an atmospheric slant depth X in units of g/cm^2. The four fit parameters are the number of particles at shower maximum, N_{max} and the depth at shower maximum, X_{max}. X_o the depth of first interaction and λ the elongation parameter.

This prediction has been confirmed in the energy range of 10^{17}eV to 10^{18}eV previously by the HiRes/MIA prototype [6]. However data now extends up to 10^{20}eV and with much greater statistics.

This paper will cover an energy range of $10^{17.5}$eV to $10^{20.0}$eV and will be compared to predicted functional forms and Monte Carlo generated using the Gaisser-Hillas equation and a full detector simulation.

Experiment and Data Set

The HiRes experiment consists of two air fluorescence detectors (HiRes-I and HiRes-II) located on Dugway Proving Ground, Utah. HiRes-I incorporates 19 mirrors in a single ring covering 3^o to 18^o in elevation. HiRes-II has 2 rings with 42 mirrors giving a 3^o to 32^o view in elevation. Each detector sees 360^o in azimuthal and each mirror has an effective area of $3.92m^2$ and a camera made of 256 PMTs each covering 1^o of the sky. Detailed detector descriptions can be found in [7].

Work presented in this paper comes from data taken in the period from 2002 to 2006 by the HiRes-II in monocular mode. To ensure that the events selected were of good quality each was required to have a track length greater than $500g/cm^2$. X_{max} must be visible $50g/cm^2$ after the beginning of the observed part of the shower

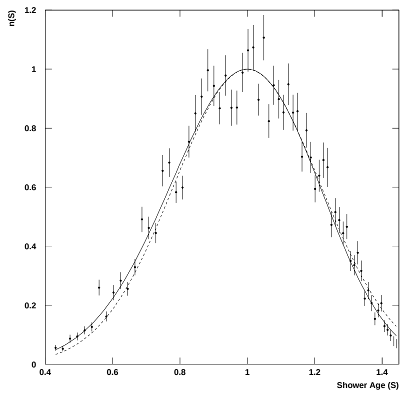

Figure 1: Typical Air Shower as measured by HiRes-II. Fit to equation 1 - $solid\ line$ and equation 4 - $Dashed\ line$

Cuts	
Selected tubes	≥ 6
Photo-electrons/degree	$> 25.$
Track length	$> 7^o$
Zenith angle	$< 80^0$
Average Cerenkov Correction	< 0.70
Geometry fit χ^2/d.o.f.	$< 10.$
Profile fit χ^2/d.o.f.	$< 10.$
X_{max}	Seen

Table 1: *Standard Cuts used in the HiRes analysis.*

and $50g/cm^2$ before its end. To minimize the amount of possible Cerenkov light ψ cannot be more than 110^o. ψ is defined as the angle between the shower and the ground in the plane of the detector and shower. These cuts were in addition to the standard quality cuts that are applied to the HiRes-II spectrum analysis [7] which are summarized in TABLE 1. A total of 11655 data events and 35966 Monte Carlo events were selected.

Normalization of Air Shower Profiles

In a data sample which varies over 3 orders of magnitude in energy the longitudinal parameters change greatly. N_{max} has a range of 10^3 and X_{max} can be found anywhere from $300gcm^{-2}$ to $1200gcm^{-2}$. For all the showers to be averaged we must find suitable ways to scale these parameters.

Each profile is locally fitted around its peak to a Gaussian function in order to determine N_{max} and X_{max}. The showers are normalized by their respective shower maximum i.e. N(X)/N_{max} denoted as n(X). All showers now equal to unity at their shower maximum.

The position of shower maximum is proportional to the log(E_o), where E_o is the primary particle energy. Longitudinal development of showers can be standardized using “shower age” [8].

$$s = \frac{3X}{X + 2X_{max}} \tag{2}$$

The development phase of the shower lies between s = 0 and 1. X_{max} is found at s = 1 and the decay phase is in the range 1 to 3. Physically a shower has a range of 0 to 2.

Applying this to a single shower gives the result seen in figure 1. The result from many showers can be averaged in bins of age giving the Average Longitudinal Shower Profile. The same technique is applied to Monte Carlo.

As shown in [6] the Gaisser-Hillas equation (1) can be written as follows

$$n(s) = \left(1 - \frac{(1-s)}{(3-s)}\frac{3T_{max}}{(T_{max}-T_o)}\right)^{T_{max}-T_o} \times e^{(3T_{max}\frac{1-s}{3-s})} \tag{3}$$

where T_{max} = X_{max}/λ and T_o = X_o/λ are the two remaining parameters. T_o is constrained to be less than $\frac{2s_{min}}{2-s_{min}}T_{max}$, where s_{min} is the lower limit of the data points, approximately 0.4. Another parametrization is the Gaussian in age

$$f(s) = exp\left(\frac{1}{2\sigma^2}(s-1)^2\right) \tag{4}$$

where the only free parameter is the width, σ.

As these showers have been fully reconstructed the energy is known. We split the data into energy bins and study the properties.

We are also able to reconstruct showers using an hourly atmospheric database instead of average atmospheric conditions. See [9] as relates to the spectrum. Monte Carlo can also be generated using the database and reconstructed in the same way.

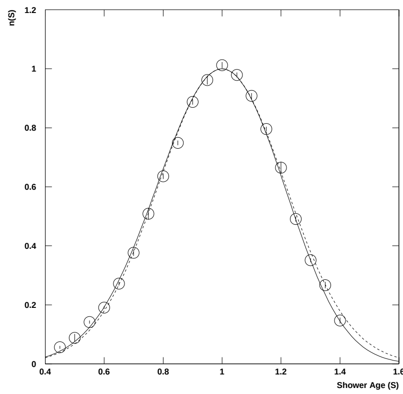

Figure 2: Average Shower $10^{19.0}$ - $10^{19.5}$eV. Fit to equation 3 (Solid line) and equation 4 (Dotted line).

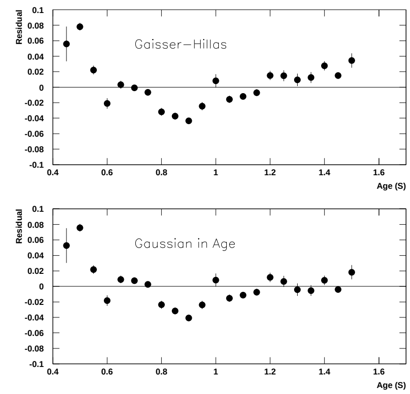

Figure 3: Residuals of the fits shown in figure 2. Upper: Gaisser-Hillas. Lower: Gaussian in Age

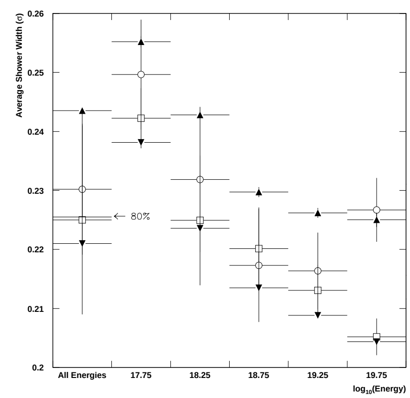

Figure 4: Average Shower widths. Empty Cirlces: $Data$ Empty Squares: $Monte Carlo$ Lower Triangles: $Proton$ Upper Triangles: $Iron$

Average Showers

When fitting the average showers care was taken to avoid biased data at extremes in age. Using the Monte Carlo we can reconstruct simulated data with no error in ψ. Reconstruction of the shower in monocular mode can be effected by poor ψ resolution. When normal Monte Carlo is compared with perfect ψ we found the deviation from the true values at low(0.7) and high(1.3) age. These areas were avoided when making fits to the average shower.

We also have a composition bias at low age and energy due to the top of the HiRes mirror at 33^o. No similar bias is seen at high age and energy.

Removing a bias in ψ also has the effect of narrowing the average shower. This narrowing is a constant 0.01 in age across all energies. This is not due to a shift in our ψ resolution which is in fact centered at 0 with a width of 5^o.

Figure 2 shows the average shower for events in the range $10^{19.0}$ - $10^{19.5}$eV. The GH equation gives a χ^2 of 46 and the Gaussian in age 63 for 20 degrees of freedom. Other energy ranges will be presented.

Figure 4 shows the result of fitting equation 4 to each half decade in energy for data and different types of Monte Carlo . The only free parameter, σ, characterizes the width and is shown as a function of energy. Data and Monte Carlo show good agreement except in the highest energy bin. Reasons for the discrepancy will be investigated in the presentation. On the figure a line is drawn 80% of distance from the Iron point the Proton point in the bin labeled All Energies. A proton fraction of 0.8 is the average composition thrown. We are correctly measuring our input.

When an hourly atmospheric database is to reconstruct events we see no significant change in the results presented. This will be shown in the talk.

Data - Monte Carlo Comparisons

Data and Monte Carlo are split into the same half-decade bins ranging from $10^{17.5}$ to $10^{20.0}$eV. An

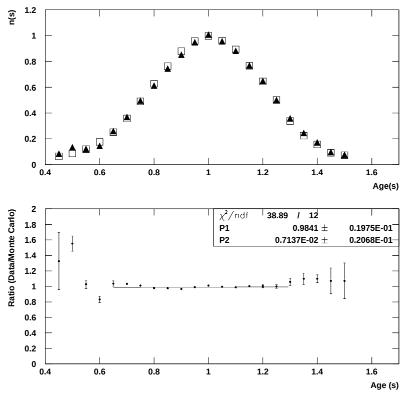

Figure 5: Data - Monte Carlo Comparison in the range $10^{19.0}$ - $10^{19.5}$eV. Upper Panel: Filled triangles are data while empty squares represent Monte Carlo. Lower Panel: Ratio of Data over Monte Carlo.

average profile was created for each energy bin. Figure 5 shows the result in the range $10^{19.0}$ - $10^{19.5}$eV. A straight line fit is made between 0.7 and 1.3 in age to the ratio of data and Monte Carlo (Lower panel figure 5). An insignificant slope is found for all half-decades.

Conclusion

We have developed a method to determine the average shower shape for the HiRes-II monocular data. The average shower is shown to be better described by the GH equation than the Gaussian in Age. Looking at Monte Carlo thrown using a GH we see no difference with that of real showers. Also when comparing shower widths against Monte Carlo of differing composition we note that the data appears to be light. The use of an atmospheric database shows no significant change in the result.

Acknowledgments

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