

The Cosmic Ray Energy Spectrum as Measured in Monocular Mode by the High Resolution Fly's Eye Experiment

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Abstract

We report on the cosmic ray energy spectrum above 3×10^{18} eV as measured by the HiRes detector running in monocular mode (BigH). We also investigate the existence of the predicted GZK cutoff at 6×10^{19} eV. Preliminary results are consistent with the Fly's Eye monocular spectrum. Construction of BigH was completed in the early months of 1997, data taking started in May of the same year. Data collected in the period May 1997 - November 1998 is used in this study. Aperture calculation, shower reconstruction techniques, and resolution issues are discussed.

1 Introduction

The High Resolution Fly's Eye (HiRes) is the successor to the original Fly's Eye Experiment, which was the first to successfully exploit the air fluorescence technique to detect ultra-high energy cosmic rays [1]. Like its predecessor, HiRes is designed for stereo-scopical observation of the scintillation light from Extensive Air Showers (EAS). Both detector sites are located at the U.S. Army's Dugway Proving Ground in the Western Utah desert. At the time of this report, the second of the two sites, HiRes-II, located at Camel's Back Ridge, is near completion and has already started limited night-sky observations. The first site, HiRes-I, located at Five Mile Hill has been taking data steadily since May of 1997. Details of the configuration of the HiRes-I site can be found in reference [2].

While the HiRes-I detector is intended to perform stereo observation in tandem with the HiRes-II detector, the two years of monocular data represent an accumulated exposure comparable to the monocular data set taken by the original Fly's Eye-I detector. While the monocular data lacks the fine resolution and redundancy of stereo data, it can nevertheless be

used to perform an early study of the energy spectrum around the cut-off, and to search for events with energies above the cut-off. This study is near completion, and some preliminary results are discussed in the last section of this paper. An outline of the data selection and the data analysis is presented in the next two sections.

2 Data selection

The transition from raw data to “reconstructible” events involves several stages of data processing and the application of various quality cuts. Firstly, for the monocular analysis, only data collected during clear weather is selected. The aperture is seriously degraded during those nights with marginal weather conditions, so that this selection rejects only a small fraction of the data set. Also, the atmospheric models used in event reconstruction and for aperture calculation provide good approximations only for clear conditions. For these reasons, only the good weather data is retained.

Secondly, most of the collected events actually result from triggers related to sky background and other noise sources. A standard ‘Rayleigh filter’ is used to reject those events whose space-time correlations are representative of random walk. We keep only those events with less than 1% probability of being random noise. In this process, about 95% of triggers are rejected.

Next, the shower-detector plane is determined and the following cuts applied: a minimum track-length cut of 6° , a “distance cut” based on track crossing angular speed ($0.17 \mu\text{s}/\text{degree}$, $\sim 3 \text{ km}$), and a cut on the average number of photoelectrons seen by triggered tubes (21 p.e.). Both the cut on distance and that on the average number of photoelectrons serve to reject low energy events. In particular, the distance cut also minimizes the number of poorly reconstructed lower energy events spilling over to the high energy region, and lead only to a negligible reduction in the detector aperture at the highest energies.

A total of 5214 events for an equivalent “On-time” of 449 hours remained after the above cuts were applied. A more stringent distance cut ($0.28 \mu\text{s}/\text{degree}$), was applied to this set leaving 2606 events for energy reconstruction. After energy reconstruction further quality cuts were applied, the most important of these is an x_{max} bracketing cut where we require that the depth at the first and last observed points along the track bracket the value of x_{max} used.

3 Data Analysis

Reconstruction of EAS observed using the air fluorescence technique can be divided into two major parts: geometrical reconstruction and shower profile reconstruction. Shower geometry is given by a shower-detector plane, $\hat{\mathbf{n}}$, and a track within the plane given by a distance of closest approach, R_p , and the angle the track makes with its projection on the ground ψ . The shower profile, defined as shower size as a function of slant depth along the track, is parameterized according to the Gaisser-Hillas parameterization in terms of x_0 , x_{max} , and N_{max} ; The depth of first point of interaction, depth at shower maximum development, and number of electrons at the point of maximum development respectively.

Traditionally, monocular track reconstruction relies on the time-fit method [1]. The combination of angular speed and angular acceleration of the observed trajectories together

determine the shower geometry: The curvature in the time vs. angle relation fixes the incline angle within the shower-detector plane, while the overall angular speed then yields the impact distance to the shower. Unfortunately, for distant events with small angular spans, there is insufficient curvature to determine accurately the incline angle. Most of the events collected by HiRes-I fall into this category. Therefore a modified approach is needed in order to perform reliably the geometrical reconstruction.

The profile-constrained geometry fit was developed by HiRes to overcome the problem of short track-length events [3]. The same reference also discusses in detail the motivation and justification for the method. Basically, while a number of different trajectories can give equally good fits to the time vs. angle relation, only a restricted range of these give showers which actually develop in the atmosphere, and with reasonable shower maximum locations. For the HiRes-I analysis, a fixed shower profile (shower size vs. slant depth relation) is assumed and a search over R_p and ψ space is performed in order to determine the geometry at which a shower with the given profile best fits the data. We use a value of $x_{max} = 825 \text{ gm/cm}^2$ for the shower maximum. This value corresponds to the expected depth of shower maximum for proton-induced showers near 10^{20} eV. By choosing this value we minimize the systematic effects in the reconstructed energy, associated with the fixed profile approach, for those events near the theoretical GZK cut-off. This procedure makes it possible to reconstruct showers with reasonable resolution, but at the expense of the ability to measure the chemical composition of the cosmic rays.

4 Results and Discussion

Events with reconstructed energies above 3×10^{18} eV which passed quality cuts were included in this analysis. A preliminary spectrum is shown in figure 1. The calculation of the flux uses aperture calculations employing a standard desert atmospheric model. As seen in figure 1, the HiRes-I monocular spectrum is in good agreement with the monocular spectrum from Fly's Eye. The energy resolution achieved by the profile constraint fit is shown in figure 2 for two mono-energetic sets of Monte Carlo events.

At the time of writing, studies are continuing to optimize the energy resolution for the reconstruction, and to better understand systematic effects on the reconstructed energy. Of particular interest is the effect of resolution tails on the search for events above the GZK cut-off. While the preliminary spectrum in figure 1 includes a few candidate events above 6×10^{19} eV, we are not yet prepared to discuss the statistical significance of events above the theoretical cut-off.

References

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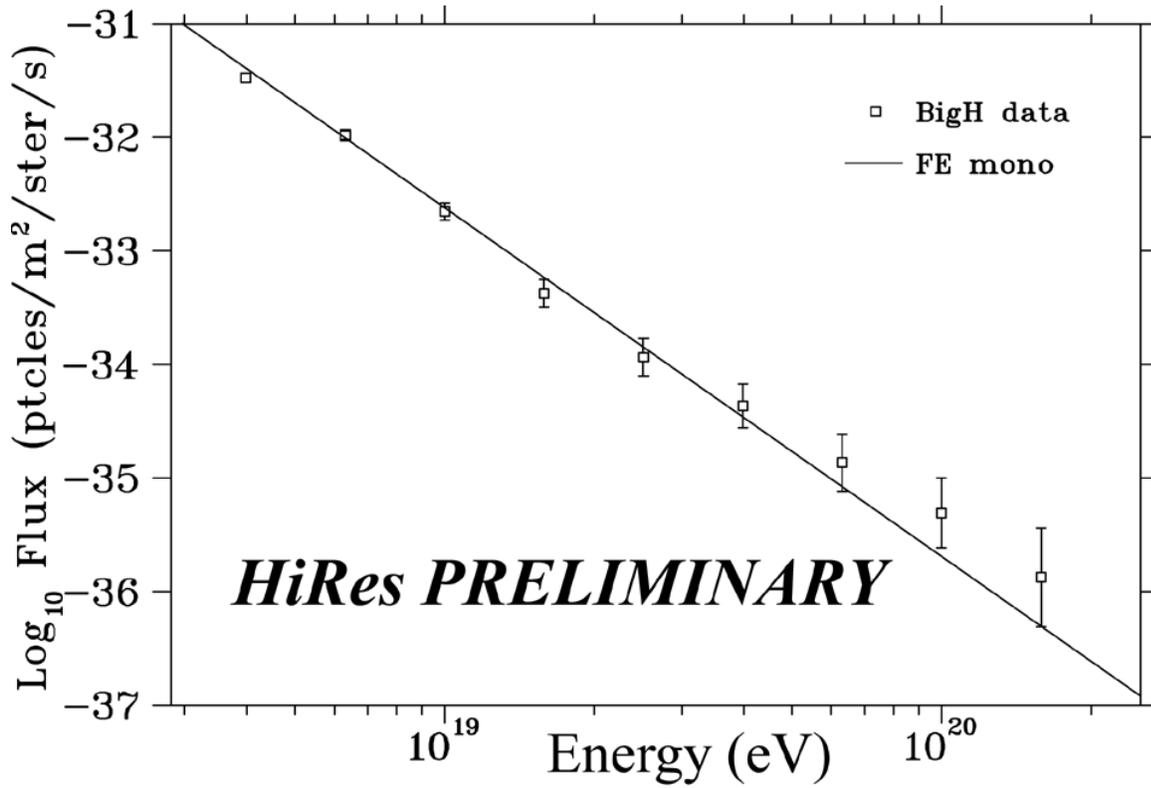


Figure 1: The points and error bars represent the monocular energy spectrum as measured by HiRes-I. The superimposed line represents the fit to the Fly's Eye monocular spectrum

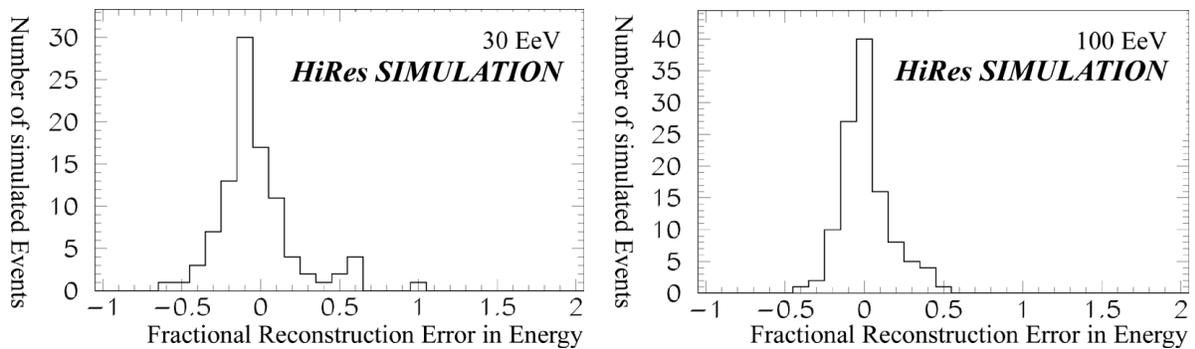


Figure 2: Energy resolution at 30 (left), and 100 EeV (right)