Using the Monte Carlo Technique in the Observation of Fluorescence from UHECRs

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FOR THE TELESCOPE ARRAY COLLABORATION

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Abstract: The aperture of a fluorescence detector varies with energy. This aperture must be estimated using a full detector Monte Carlo simulation. The reliability of this estimate is gauged by comparing distributions of measurable quantities between real and simulated data. The Monte Carlo simulation will be presented and plots comparing data and Monte Carlo distributions will be shown.

Keywords: UHECR, fluorescence, extensive air shower, Monte Carlo simulation.

1 Introduction

The Telescope Array (TA) is an experiment designed to measure the energies, composition and arrival directions of ultra-high energy cosmic rays (UHECRs). Located in Millard County, Utah, it consists of 38 nitrogen fluorescence detectors (FDs) overlooking an array of 507 surface detectors (SDs). Detection in "hybrid" mode (using the combination of FD and SD detection techniques) provides independent measurements of the development of a cosmic ray-induced shower in air in addition to its footprint on the ground. In this way, measurements taken using both techniques can be cross-checked and cross-calibrated, thereby greatly improving measurements of geometry and energy as compared to either technique alone. The FDs have been online and taking data since November 2007; the SDs since April 2008.

In this paper, we report on the results of our work with the two southern FD sites of the array. We present the data and the techniques used to calculate the energies of UHECRs and detector aperture, emphasizing the importance of a full-detector Monte Carlo simulation in the determination of aperture.

2 TA Fluorescence Detectors

The FDs are situated into three stations, known as Middle Drum (MD), Black Rock Mesa (BR) and Long Ridge (LR). Each FD is composed of a segmented spherical mirror projecting onto an array of 256 hexagonally close-packed photomultipliers (PMTs). The detectors' orientations are fixed and they are designed so each PMT views 1° of solid angle in the sky. MD sits to the north and houses 14 FDs viewing a region from 3° to 31° in elevation and 110° in azimuth. It uses refurbished hardware from the High Resolution Fly's Eye I site, so its data acquisition and analysis is identical to that used by HiRes [1]. The sites at BR and LR were designed specifically for the TA experiment. Each contains 12 telescopes utilizing flash ADC data acquisition systems operating at 10MHz and mirrors 40% larger than those at MD [2].

3 The FD Simulation

3.1 Background

The initial collision of an UHECR with Earth's atmosphere produces hundreds to thousands of high energy particles, mainly πs. The π^0s quickly decay into gamma rays, each subsequently producing $e^+ - e^-$ pairs. These ionize nearby nitrogen and oxygen atoms, which produce fluorescence light as they de-excite. Some of the $\pi^{\pm}$s decay into $\mu^{\pm} - \nu_\mu$ pairs, but they usually live long enough to collide with more atmospheric matter and propagate what is called the extensive air shower (EAS). Eventually, ionization losses dominate and the energy per particle is insufficient to sustain the shower.

Drawing from cascade theory, Thomas Gaisser and Anthony Hillas suggested the following expression to represent the longitudinal particle density of an EAS as a function of atmospheric matter traversed [3],

$$N_{\text{ch}}(X) = N_{\text{max}} \left(\frac{X - X_0}{X_{\text{max}} - X_0} \right)^{\frac{X_{\text{max}} - X_0}{\Lambda}} e^{-\frac{X - X_{\text{max}}}{\Lambda}} \qquad (1)$$

Known as the Gaisser-Hillas (GH) formula, equation (1) is a function of four parameters: The number of charged particles present in the air shower at its maximum intensity (N_{max}), the depth in the atmosphere where the maximum occurs (X_{max}), the depth where the initial interaction occurs (X_0), and the shower development parameter (Λ), which is related to the particles' characteristic interaction length. Figure 1 shows an example shower profile for an event seen in data, fit to a GH function.

Fluorescence light is emitted isotropically from points near the air shower's axis. The total fluorescence yield is proportional to the local ionization energy deposited, which is the product of the number of charged particles present and their mean ionization loss rate. In addition to fluorescence light, charged particles at high energies also produce Cherenkov radiation. Unlike fluorescence yield, Cherenkov production is proportional to the number of charged particles, not the energy deposited.

Detector response changes dramatically with cosmic ray primary energy and air shower geometry. Furthermore, atmospheric conditions and aspects of the detector hardware weigh heavily when measuring the properties of the EAS. Integral to the calculation of an FD aperture is the development of a good detector Monte Carlo program which accurately predicts the light produced by extensive air showers, simulates the detector response to this light and, when analyzed, reproduces all aspects of the data.
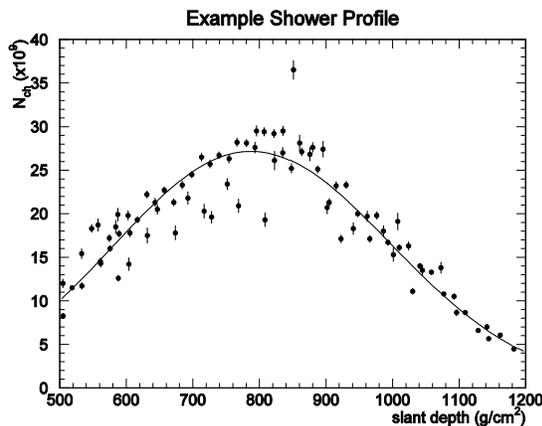

Figure 1: Example of a shower profile. Points with error bars are the estimated number of charged particles; the curve is the best fit GH formula.

3.2 The Monte Carlo Simulation

Using the energy spectrum as measured by the HiRes experiment, we "throw" events isotropically according to actual detector on-times from a library of GH parameters taken from CORSIKA simulations of ultra-high energy cosmic ray extensive air showers. We follow the development of the shower in 1 g/cm^2 steps calculating the appropriate amounts of fluorescence and Cherenkov light using actual Radiosonde measurements of atmospheric temperature and pressure. Fluorescence light is scattered isotropically to the detector; Cherenkov light builds along the track and is scattered using the appropriate Rayleigh and aerosol scattering functions. All attenuations due to Rayleigh, aerosol and ozone scattering are considered.

Using actual measurements of mirror reflectivity, PMT response and quantum efficiency, ray-tracing is performed to find the light that reaches the detector and determine the appropriate acceptance in the photomultipliers. The actual trigger conditions of the detector and electronics response is simulated, storing the resulting signal in the same format as the raw data.

3.3 The "Inverse Monte Carlo" Technique

The FDs measure only the light emitted by high-energy particles interacting in the atmosphere. As described above, relating the amount of light detected at the mirrors as a function of time to the number of charged particles at a given depth along the track is therefore a non-trivial task.

For an air shower with given geometry, the ray-tracing routines from the Monte Carlo simulation are used to estimate the "acceptance", the fraction of fluorescence and Cherenkov light produced by the air shower which is collected by the FDs. The set of GH parameters that describe the shower's longitudinal development are found by performing a least-squares fit of the detector response to its simulated response, minimizing the χ^2,

$$\chi^2 = \sum_{i=1}^{N_{\text{gt}}} \frac{\left(\tilde{S}_i - S_i \right)^2}{\delta \tilde{S}_i^2 + \delta S_i^2} \qquad (2)$$

where S_i stands for the signal received by PMT channel i and $\tilde{S}_i$ represents the corresponding simulated signal. The uncertainty in the observed signal, δS_i, comes from the statistical fluctuations from signal and background noise. The uncertainty in the simulated signal has an additional term to account for the relative binomial error in the acceptance found in ray-tracing. The summation is taken over the number of tubes used to fit the shower geometry.

Since the best-fit Gaisser-Hillas profile for a shower is only weakly dependent on X_0 and Λ, average values of -60 and 70 g/cm^2 are used. Using a fitting routine, air showers are simulated using variable N_{max} and X_{max} until the χ^2 sum in equation (2) is minimized.

3.4 Analysis of Data and Monte Carlo

FD aperture is a function of UHECR energy and geometry. Intuitively, higher energy cosmic rays will produce brighter air showers which will be observed from greater distances. The FDs will also be more sensitive to showers which propagate perpendicularly to their viewing directions. To measure aperture, air shower events are generated using isotropic geometry in the parameter space $A\Omega$, which is set well beyond detector sensitivity. The FD response to these events is simulated and processed using the same chain of analysis used for real data. Aperture is the ratio of these events which pass the full set of quality cuts to the total generated within a given energy range E_i,

$$\text{Ap}(E_i) = \frac{N_A(E_i)}{N_T(E_i)} A\Omega \qquad (3)$$

In order to gain a consistent measurement of detector aperture, simulated data must be passed through the exact same series of analysis programs used for real data and therefore real and simulated raw data must be indistinguishable. Hence, the accuracy of the aperture measurement is limited to the agreement between data and Monte Carlo. Figure 2 is a comparison of the distributions in data and MC of the cosmic ray impact parameter, R_P. Points with errors are data and the histogram is MC, which is scaled to the same area as the data distribution. Likewise, Figure 3 is the data-MC comparison of ψ, the angle formed by the shower axis with the ground in the shower-detector plane. Figure 4 is the resulting measurement of FD aperture using MC simulation. The errors increase with energy because events are simulated according to the latest published energy spectrum results and higher energy events occur less frequently in nature.

Acknowledgements

References

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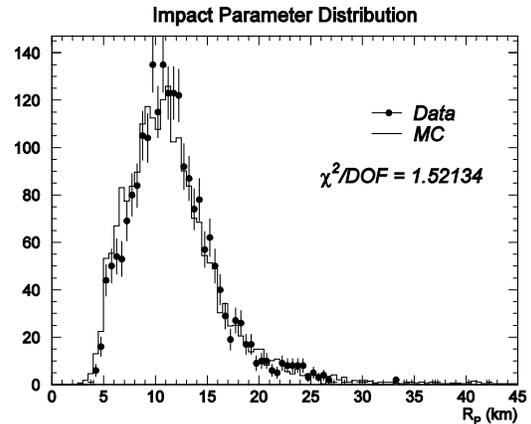[3] T. Gaisser and A.M. Hillas, Proc. 15th ICRC, 1977

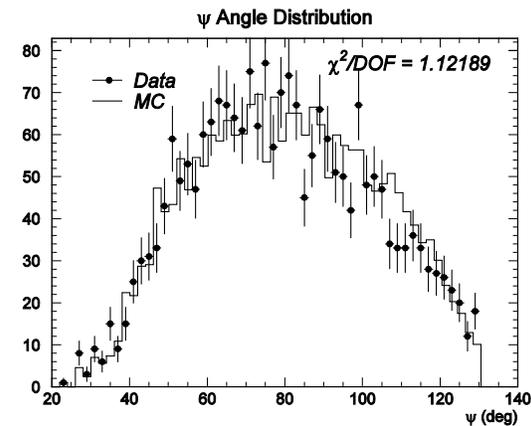Figure 2: Data-MC comparison of the distribution of impact parameter R_P, observed at Long Ridge.

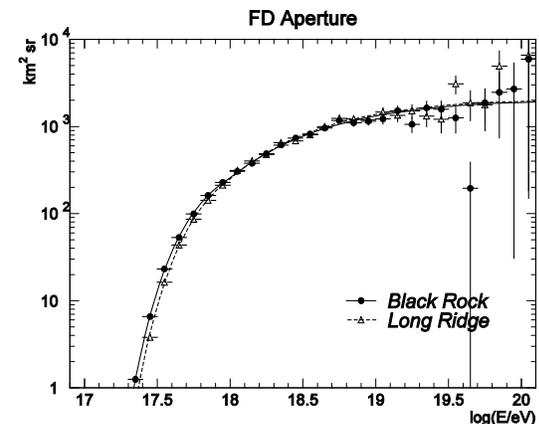Figure 3: Data-MC comparison of the distribution of ψ, observed at Long Ridge.

Figure 4: Preliminary aperture measured using Monte Carlo simulation of detector response.