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The measurement of UHECR spectrum with the HiRes experiment in stereo mode

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In this paper, the energy spectrum of UHECR with energy above $10^{18.2}$eV has been measured with HiRes detector in stereo mode. The cosmic ray events reconstruction has been presented briefly. A new direction reconstruction method has been introduced. The resolution of arrival direction is about 0.44 degree and the energy resolution is about 10%. The detector aperture is studied in detail, and an aerosol free aperture is given. At last, the result on the UHECR spectrum is presented and its uncertainty is discussed.

1. Introduction

To understand the origin, propagation of UHE cosmic rays and to judge whether the GZK-cutoff exists, one important way is to measure the energy spectrum of UHECRs. The HiRes detector [1,2] is a fluorescence detector. It is designed to study the energy spectrum, composition and anisotropy of UHE cosmic ray in good resolution. In this experiment, the calorimeter is the atmosphere. By measuring the amount of air fluorescence light, the energy in an extensive air shower can be determined. The detector is located at the U.S. army Dugway proving grounds in Utah. It consists of two sites: HR1 and HR2. They are separated by a distance of 12.6 km. HR1 consists of 22 mirrors. The mirrors are configured in a *ring* that covers the full azimuthal range. The elevation angle coverage is from 3° to 17°. It adopts *sample and hold* electronics system. HR2 employs 42 mirrors, and it has two *rings* with full azimuthal angle and with elevation angle from 3° to 31°. Its electronics readout system is *FADC*. In each mirror focus plane, there is a cluster which consists of 256 photomultiplier tubes. Every PMT covers 1°×1° range of the sky. The two sites are operated independently, the data collected can be analyzed either in monocular mode for each site, or together in stereo mode. The results of the energy spectrum in monocular mode have been reported in [2,3]. The stereo mode will bring an improved resolution in reconstructed arrival direction and primary energy in comparison to the monocular mode. This work is based on the stereo mode analysis.

The paper is arranged as follows: In Section 2, data reconstruction is described. Then the detector simulation is presented in Section 3. The comparison between real data and Monte Carlo data is also given in Section 3. The detector aperture estimation is introduced in Section 4. Finally, the energy spectrum and its uncertainty are given in Section 5.

2. Data reconstruction

2.1. Geometry reconstruction

The tubes triggered by cosmic ray events are in regular sequence by space, also by time, so the noise tubes are easy to get rid of. We fit the Shower-Detector-Plane of HR2 by using the triggered tube pointing direction and weighting every tube with its signal.

For HR1's plane reconstruction, the traditional method is similar to that of HR2. As mentioned above, HiRes1 covers only 14 degree elevation angle. Generally, its track-length is short. So the HR1 plane determined by the traditional method

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is not good. While HR2 has two rings and uses $FADC$ readout system. It has higher time resolution. We use the HR2 timing information to modify the HR1 plane. In this process, the central vector of HR1 is also used.

From the intersection of the two Shower-Detector-Planes, we obtain the arrival direction of the shower. Using this method, the direction resolution is better improved. It is about 0.44°, see Fig. 1.

2.2. Energy reconstruction

Once the geometry of the shower is known, we fit the profile of the shower by Gaussian-in-Age function after considering the light production and propagation, and get N_{max}, X_{max} and σ_s of the shower profile. This fit determines the parameters of an air shower that most likely could have produced the detected signal. We integrate the final fitted Gaussian-in-Age function over all s (shower age) and multiply by the average energy loss per particle (2.379 Mev/g/cm^2) to determine the visible shower energy. The visible energy is then corrected for energy carried off by unobservable particles to give to total shower energy.

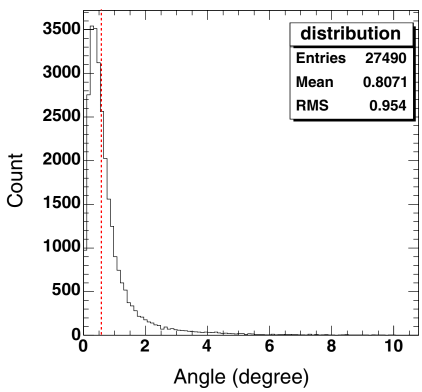

Figure 1. The distribution of the angle between the shower direction thrown and reconstructed.

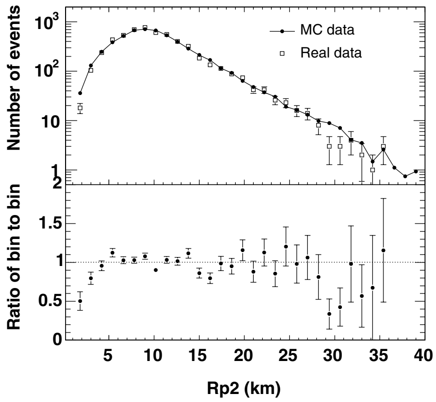

Figure 2. Rp2 comparison between MC and data. Top panel: the distribution of Rp2. Square points represent data and circle points represent MC. Bottom panel: the ratio of data to MC by bin. The number of MC events has been normalized to equal that of data events.

3. Detector simulation

The detector simulation serves three important functions: the detector aperture estimation, the resolution study for checking the reconstruction method and the comparison between the real data and Monte Carlo data. For all of the above purposes, the detector simulation has to mimic the real detector as close as possible. The simulated event has to be representative of real event. In the simulation, the showers come from the library which has sets of showers generated using CORSIKA[4] and QGSJet[5]. The following parameters are used in the simulation code. The initial flux J_0 $2.0 \times 10^{24} eV^2 m^{-2} s^{-1} sr^{-1}$ is adopted. Hourly exposure time according to real experiment, hourly atmospheric condition, daily electronics gain and radiosonde data (atmospheric pressure and density) are used in the process of simulation.

To understand how well the geometry and physics quantities are determined, we make some resolution studies and make some comparisons

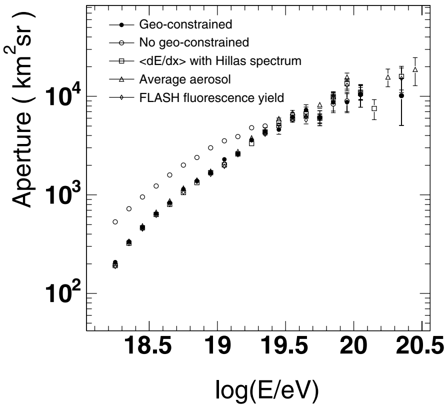

Figure 3. The aperture uncertainty of HiRes detector.

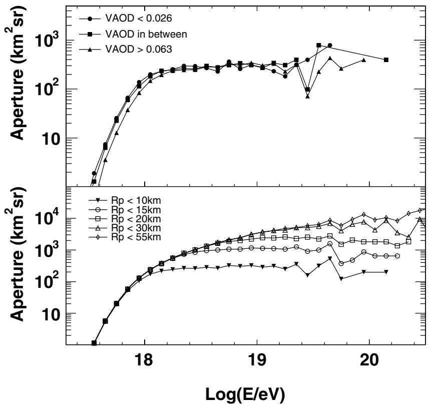

Figure 4. Top: The apertures at 3 kinds of different weather condition within the range of 10km for R_p. Bottom: The average apertures with R_p below 10km, 15km, 20km, 30km and 55km, respectively.

between MC and data. Before doing so we apply some cuts. If vertical atmospheric optical depth (VAOD) is larger than 0.1 in an hour, the events during this hour are cut. The events without good profiles are also cut. For an event, if Cerenkov light contamination is greater than 30%, the event is cut. For MC events, all reconstruction procedures are the same as to the real data. Fig. 1 shows the arrival direction angular resolution. The X-axis is the angle between the thrown direction and the reconstructed direction. From this plot, we can see the median value is 0.52 degree. This angle distribution corresponds to a two-dimensional Gaussian distribution. According to this value, the sigma of the two-dimensional Gaussian distribution is 0.44 degree. The following resolutions have also been studied: the R_p (impact parameter), shower N_{max}, shower energy and shower X_{max}. They are 0.5%, 7.0%, 30gm/cm^2 and 10%, respectively.

In order to test how realistically the simulation reflects the shower development in the air and the responses of the detector, we make many comparisons between MC and data, such as zenith angle, azimuth angle, track-length, triggered tubes per degree and R_p . Fig. 2 shows the R_p comparison of HiRes2 between MC and data. From this figure, one can see that they agree very well. All other observed parameters are compared and show the similar agreement in comparisons between data and MC.

4. Aperture estimation

Through the resolution study and comparison between MC and data, it is possible that we can estimate the detector aperture very well using Monte Carlo data. This results in an aperture shown in Fig. 3 with open circles. Only statistic errors are presented.

We study the atmospheric effect on the aperture. If the atmosphere is clear, the aperture of the detector is larger that that there are more aerosol contents in the atmosphere. We manage to find a stable and an aerosol free aperture. We estimate the apertures at different weather conditions with certain constraints on the geometrical size of the aperture to cut the edge of the field of view of the detector where the shower detection efficiency is largely affected by atmospheric effects. The top panel of Fig. 4 shows

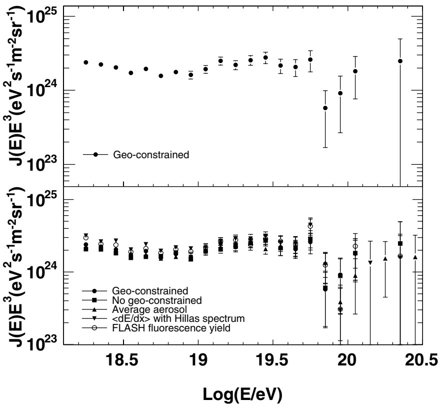

Figure 5. The measured energy spectrum of UHECR. Top: The spectrum measured after geometry-energy constrained. Bottom: The spectrum measured at different conditions.

the apertures at 3 kinds of atmospheric conditions within the range of 10 km for R_p. From this plot, one can see that the atmosphere does affect the aperture. But if the energy is greater than $10^{18.2}$eV, the atmospheric effects are largely suppressed, and the apertures become stable. The average aperture with R_p below 10km is plotted in Fig. 4 bottom panel. We make some similar studies with different geometry constrains, such as 15km, 20km, 30km, 55km. The apertures have the same feature that within a certain range, if energy is above a value, the aperture is stable and aerosol free. The average apertures with R_p below 15km, 20km, 30km and 55km are shown in Fig. 4 bottom panel. According to the relation of R_p and energy above which the aperture becomes aerosol free, we set R_p constraints as functions of energy, and get an aerosol free aperture, see Fig. 3 (filled circles, referred to as geo-constrained).

5. Energy spectrum and its uncertainty

The cosmic ray flux is measured by using the HiRes data with a correction of estimated aperture. The spectrum is shown in Fig. 5. The flux has been multiplied by E^3. Only the statistical error is included. The exposure time is 8.6×10^6 seconds. 4 events with energy above 100 EeV have been observed. At a few EeV, a dip can obviously been seen. The GZK feature is indicated.

The main systematic uncertainty of HiRes monocular spectrum has been summarized in [2]. In our analysis, we use the fluorescence yield measured by Kakimoto et al. [6], mean dE/dX based on modern simulation of air showers and hourly atmospheric quality. We carefully studied the uncertainties caused by fluorescence yield, mean energy loss per particle, and atmospheric quality using the fluorescence yield measured by FLASH experiment [7], mean dE/dX calculated with Hillas electron spectrum and average atmospheric condition, respectively. The aperture estimations are showed in Fig. 3 and they are all geo-constrained. The corresponding spectra are plotted in Fig. 5. All spectral structures and features remain the same as that with default assumptions.

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