Small-Scale Anisotropy Studies of the Highest Energy Cosmic Rays Observed in Stereo by HiRes

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Abstract

The High Resolution Fly's Eye (HiRes) experiment is a stereo air fluorescence detector for the study of cosmic rays with energies above 10^{18} eV. When a cosmic ray-induced air shower is seen by both detectors, the reconstruction of the cosmic ray arrival direction has a typical uncertainty on the order of 0.5°. This makes HiRes well suited for anisotropy studies. We present here an analysis of the distribution of ultra-high energy cosmic ray arrival directions observed in stereo by the HiRes experiment. In particular, we search for anisotropies in the distribution on small scales ($< 5°$) and at the highest energies ($> 10^{19}$ eV), where the prospects for identifying point sources seem most promising.

1. Introduction

Identifying the sources of ultra-high energy cosmic rays (UHECR) remains one of the central challenges in the field. Source identification would tell us a great deal about acceleration mechanisms which present physical theory is hard-pressed to describe, or it may reveal entirely new physics.

Unfortunately, source identification has thus far remained elusive. The distribution of arrival directions of UHECRs is remarkably isotropic, and no correlations with astronomical objects have been confirmed. However, arrival directions do not necessarily point back to sources, because charged cosmic ray primaries will suffer deflections traveling through galactic and intergalactic magnetic fields. The strength of intergalactic magnetic fields is not well established, so the size of these deflections is difficult to ascertain.

The highest energy cosmic rays, above 10^{19} eV, are therefore a natural regime in which to search for small-scale anisotropy. Having suffered the smallest deflections while in transit, their arrival directions are more likely to correlate with their origins.

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2. HiRes

The HiRes experiment consists of two air fluorescence detectors situated 12.6 km apart on the U.S. Army Dugway Proving Ground in Utah. A cosmic ray primary interacting in the upper atmosphere induces an extensive air shower which the detectors observe as it develops through the atmosphere. From this signal, information about the arrival direction, energy, and composition of the cosmic ray primary can be inferred. When the air shower is observed by both detectors, the stereo reconstruction results in excellent angular resolution of the arrival direction.

HiRes has been observing in stereo since November 1999, and the data set through February 2003 includes 164 well-reconstructed events above 10^{19} eV. All of these events have estimated energy uncertainties $< 20\%$ and angular uncertainties $< 2^\circ$. Moreover, for 67% of these events, the angular uncertainty is less than 0.75°. The HiRes data thus provides a unique opportunity for small-scale anisotropy studies.

3. Method

A standard tool for anisotropy searches is the two-point correlation function. We consider all pairs of events in the data and let $N(\theta)$ equal the number of pairs whose angular separation is between θ and $\theta + \Delta\theta$. We also evaluate $N_{mc}(\theta)$ for an equal number of events simulated in a Monte Carlo with the same detector exposure; we calculate the average $\hat{N}_{mc}(\theta)$ over many Monte Carlo trials and the standard deviation $\sigma_{mc}(\theta)$. The usual estimator for the correlation function is then defined as $w(\theta) = N(\theta)/\hat{N}_{mc}(\theta) - 1$.

Fig. 1 shows the two-point correlation function for HiRes stereo events with energies above 10^{19} eV, along with 1σ fluctuations. Clustering would show up as an excess at the smallest angles over the statistical fluctuations. No significant excess is observed.

What about the possibility of a clustering signal at higher energies? A limitation of the correlation function which we wish to overcome is the necessity of choosing an energy threshold E_s to define the data set. Two competing forces motivate the choice of E_s. On the one hand, we anticipate that clustering may only become apparent at the highest energies, when deflections by magnetic fields are sufficiently small; on the other hand, the statistical power weakens as we limit the study to higher energy events.

A similar dilemma exists for the choice of the smallest angular separation θ_s which would maximize the significance of clustering in the first bin. A clustering signal from point sources might be strongest at the angular resolution of the detector, or it might be spread over many degrees by magnetic fields.

Therefore, we perform a scan simultaneously over energy thresholds and

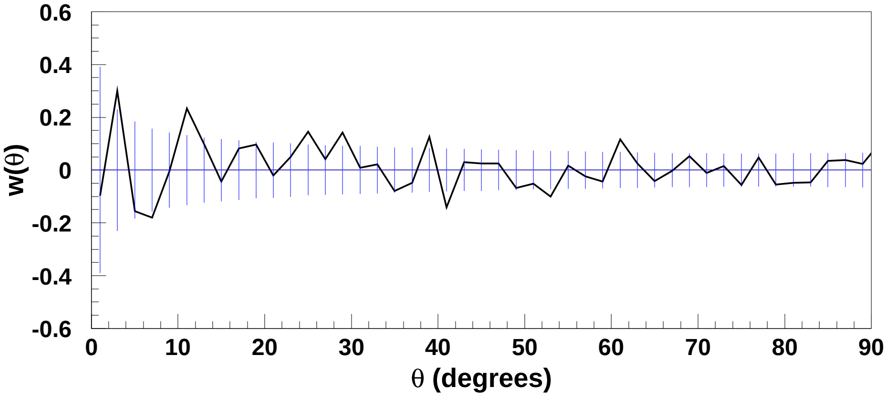

Fig. 1. Two-point correlation function for HiRes stereo events above 10 EeV. (Vertical bars indicate 1σ fluctuations.)

separation angles to find the E_s and θ_s which maximize the clustering signal. This scanning technique requires careful evaluation of the final significance we attach to any findings.

In practice, we do not scan directly over energy thresholds E_s: rather, we rank the events by energy and scan over events N_s. That is, for each N_s and θ_s, we restrict ourselves to the N_s highest-energy events, and count the number of pairs n_p separated by less than θ_s.

We define $P_{mc}(\theta, N, n)$ as the probability of finding among N events exactly n pairs with separations less than θ. This is determined from Monte Carlo trials with the same exposure as the detector. Then the probability of observing n_p or more pairs at (θ_s, N_s) is:

$$P_{data}(\theta_s, N_s) = \sum_{n=n_p}^{\infty} P_{mc}(\theta_s, N_s, n) = 1 - \sum_{n=0}^{n_p-1} P_{mc}(\theta_s, N_s, n). \tag{1}$$

$P_{data}(\theta_s, N_s)$ has a minimum for some θ^*, N^*. These are the thresholds which yield the most significant potential signal of clustering.

Finally, we perform the same scan over n_{mc} Monte Carlo data sets, identifying the minimum probability $P_i^* = P_i(\theta_i^*, N_i^*)$ for each trial and counting the number of trials n_{mc}^* for which $P_i^* \leq P_{data}(\theta^*, N^*)$. We evaluate the chance probability of finding the clustering observed in the data *at any* N_s *and* θ_s in the scan:

$$P_{ch} = \frac{n_{mc}^*}{n_{mc}}. \tag{2}$$

4. Results

We perform this scan on the HiRes stereo data above 10^{19} eV. The results are shown in Fig. 2. The chance probability of the clustering signal observed

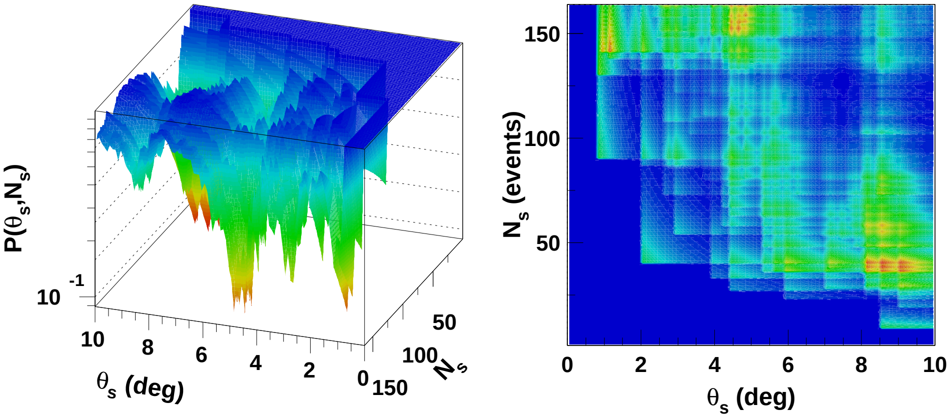

Fig. 2. Scan of HiRes stereo events above 10^{19} eV. $P(\theta^* = 8.6°, N^* = 41) = 0.089$ with $n_p = 12$ pairs. (N^* corresponds to $E^* = 22.35$ EeV).

in the data is $P_{ch} = 90\%$, consistent with no small-scale anisotropy among the highest energy events. This conclusion is stronger than the one drawn from the correlation function, because the scan is sensitive to clustering at any energy threshold above 10^{19} eV.

Comparison of this result with respect to the evidence for clustering found in the AGASA data [3-5] involves a number of considerations. Among them are different sizes of the event samples at high energies, the possibility of the reconstructed energies being shifted between the two experiments [1], and the different angular resolutions. These considerations will be discussed at the conference.

We also investigate the recent claim [2] that gamma-ray-loud BL Lacs correlate with the highest energy cosmic rays. Details will be presented at the conference.

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