

Search for Anomalous Shower Speeds in the HiRes Data Set

S.A. Blake* and Charles C.H. Jui* for the HiRes Collaboration

*University of Utah, Salt Lake City, Utah.

Abstract. The HiRes detector performed stereoscopic observations of Ultra High Energy Cosmic Rays (UHECRs) from 1999 to 2006, recording a data set with stereo aperture of UHECRs with energies down to 10^{18} eV. The coincident observation from two sites allows for geometrical reconstruction without the use of any timing information. This feature permits the direct measurement of shower propagation speed. Using this measurement of shower speed, the HiRes data was examined for possible "exotic" events. The first results of this search will be reported.

Keywords: HiRes, Shower Speed

I. INTRODUCTION AND MOTIVATION

From 1999 to 2006, the HiRes detector observed Ultra High Energy Cosmic Rays (UHECRs) above the Utah desert. The HiRes experiment was designed to view events with energies above $10^{18.5}$ eV. Among the primary goals was the search for the GZK cutoff [1] and measurement of the spectrum [2] of UHECRs above this energy.

The HiRes detector consisted of two fluorescence detectors separated by approximately 12.6 km. This stereo configuration allowed for showers to be examined based on their propagation speed. For monocular fluorescence detectors, the speed of the Extensive Air Shower (EAS) must be assumed in order to reconstruct the geometry of the shower. With two "eyes" however, the geometry of the shower can be calculated without needing to assume the speed of the shower.

This property of the HiRes experiment allows for the possible detection of types of new particles. Light nuclei such as iron and proton must be moving at near the speed of light to reach the energy range HiRes observed. As particles produced in the EAS are also highly relativistic, the shower also propagates at near the speed of light. An EAS with a propagation speed higher than the speed of light could indicate the existence of exotic particles like Tachyons or new physics at work. If the propagation speed of the EAS is significantly lower than the speed of light, this could indicate exotic forms of matter like strangelets [3].

The HiRes experiment presented a unique opportunity to look for possible signals of these types of particles. Because the particles are still theoretical, it is not certain they would interact with the atmosphere in a manner that could be observed by the HiRes detector. This study did not attempt to answer that question. Instead, the focus of this study was to see if possible candidates exist in

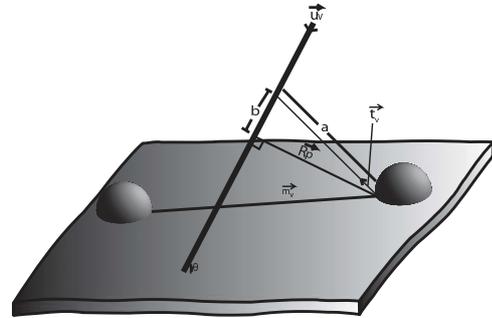


Fig. 1: Illustration of geometry from a HiRes detector.

the HiRes data set based on shower propagation speed. In this paper, the first results for this search are reported.

II. METHOD

Each telescope in the HiRes detector consisted of a 3.72 m^2 mirror focusing light onto a camera consisting of 256 phototubes. The number of telescopes differed between the two sites, but both were arranged in a ring configuration. The first site, HiRes-1, was located on Little Granite Mountain and viewed the sky from approximately 3 to 17 degrees in elevation. The second site, HiRes-2, was located on Camel's Back Ridge and viewed the sky from approximately 3 to 31 degrees elevation. Both sites had almost full 360 degrees azimuthal coverage.

For every triggered tube in the event, this configuration resulted in a known pointing direction and trigger time. Fig. 1 illustrates the geometry from a HiRes detector. Here, \vec{u}_v is a unit vector pointing in the direction of the shower. \vec{R}_p is a vector from the center of the detector to the closest point of approach for the shower. \vec{m}_v is a vector from the center of the HiRes coordinate system to the location of an individual telescope. \vec{t}_v is a vector with the pointing direction of a tube relative to the telescope. The distances a and b are calculated distances using the above vectors and will be discussed shortly.

Using the pointing direction of the tubes, a plane called the Shower Detector Plane (SDP) that intersects with the triggered tubes was calculated for each detector. The shower axis is described by \vec{u}_v and a point of impact on the ground. It is located somewhere on the SDP. For monocular reconstruction, timing information is used to determine where on the SDP the shower axis lies. With stereo information, the shower axis can be entirely determined by finding the intersection of the planes from each of the detectors. This is shown in figure Fig. 2. Here the shower axis is labeled as EAS Trajectory and each

TABLE I: Summary of data selection cuts made for speed analysis

Quantity Name	Quantity Meaning	Value (events kept if)
NPE	Photoelectrons per tube	NPE > 1.0
hr1tubes	Good tubes recorded in event for HiRes-1	hr1tubes > 3
hr2tubes	Good tubes recorded in event for HiRes-2	hr2tubes > 6
hr1track	Observed event track length in degrees	$3^\circ < \text{hr1track} < 36^\circ$
hr2track	Observed event track length in degrees	$6^\circ < \text{hr1track} < 57^\circ$
Opening Angle	Angle between two planes (adjacent to α in Fig. 2)	$7.5^\circ < \text{Opening Angle} < 172.5^\circ$
$hr1\sigma_{boot}$	Standard deviation of shower speed calculated using the HiRes-1 detector	$hr1\sigma_{boot} < .0025$
$hr2\sigma_{boot}$	Standard deviation of shower speed calculated using the HiRes-2 detector	$hr2\sigma_{boot} < .0027$
Ψ	Angle between verticle and shower axis	$30^\circ < \Psi < 120^\circ$
Θ	Angle between ground and shower plane	$\text{Theta} < 70^\circ$
track	Track Length in degrees of shower in telescope	track > 8°
\vec{R}_p	\vec{R}_p vector shown in Fig. 2)	$\vec{R}_p > 2.5 \text{ km}$

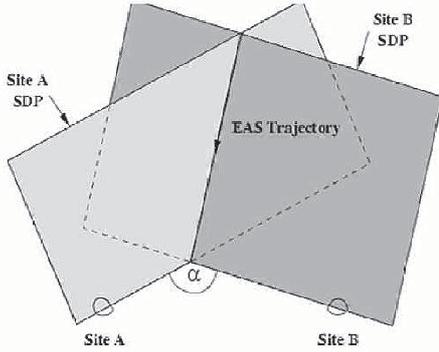


Fig. 2: Illustration of finding EAS trajectory by crossing Shower Detector Planes(SDP).

plane is labeled appropriately.

Once the shower geometry was determined, the shower speed was calculated. This happened in four basic steps. First, the distance along the shower axis from a reference point was calculated (b in fig. 1). Second, the distance light traveled from the shower axis to the detector was calculated (a in fig. 1). Next, the trigger time for each tube was corrected for this travel distance using Equation 1.

$$t_c = t_t - \mathbf{a}/c_{air} \quad (1)$$

In this equation, t_t is the tube trigger time, t_c is the corrected tube time, \mathbf{a} is the distance illustrated in fig. 1 and c_{air} is the speed of light in air. In the final step, the speed was calculated by fitting all resulting tube times to a straight line using a least χ^2 fit. This process was performed individually on each detector, resulting in a speed for both HiRes-1 and HiRes-2.

As this was a search for new physics, a large amount of effort was put into minimizing possible sources of error. Much of this effort will be discussed in the section on Monte Carlo results. It is worth noting the parts directly related to shower reconstruction here. This included removing "noise" tubes, or tubes with a high probability of having been triggered by something other than the EAS. Noise tubes were removed using an iterative fitting process. During this process, the orthogonal distance of each tube from the fit was calculated. The standard

deviation of the set these orthogonal distances was then calculated. After this, tubes with an orthogonal distance greater than 5 standard deviations from the fit were removed.

In order to estimate the error of the fit, a bootstrap method was used. Here, the total number of good tubes in the shower was recorded. A new shower was created with the same physical parameters as the old shower but with no triggered tubes. Tubes were then selected at random from the set of good tubes in the original shower. This was repeated until the new shower had an equal number of good tubes as the old shower. The shower was then refit and the resulting speed was recorded. This process was repeated 100 times, after which the RMS of the resulting set of speeds was calculated. This quantity σ_{boot} was used as a rough estimation in error of the speed of the shower.

III. MONTE CARLO SIMULATION

As mentioned in the preceding section, a large amount of effort was put into validating the process used to calculate the speed of the shower. This was done using a series of showers generated using Monte Carlo methods. Several sets of Monte Carlo showers were generated for this purpose. First, a large set of 50,000 events was generated using shower speeds of .299 m/ns (the canonical speed of light) and spanning the full energy range of the HiRes detector. These events were run through the exact same processing steps as the real data

The resulting event distributions were then examined to find cut parameters that impact the overall accuracy of the shower speed measurement. This process resulted in a set of cuts which were used to reject showers with high probabilities of fitting the speed incorrectly. These are shown in Table I.

After these cuts were made, one further cut on the normalized difference in speeds between the two detectors and the error calculated through the bootstrap method was made. The exact equation used is shown in Equations 2 and 3.

$$\delta_n = \frac{\text{speed}_{HR1} - \text{speed}_{HR2}}{\sqrt{(\sigma_{HR1}^2 + \sigma_{HR2}^2) + 2 * Cov(\sigma_{HR1}, \sigma_{HR2})}} \quad (2)$$

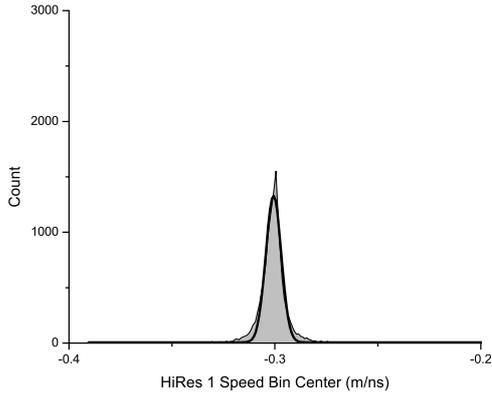


Fig. 3: Distribution from HiRes-1 Monte Carlo Data

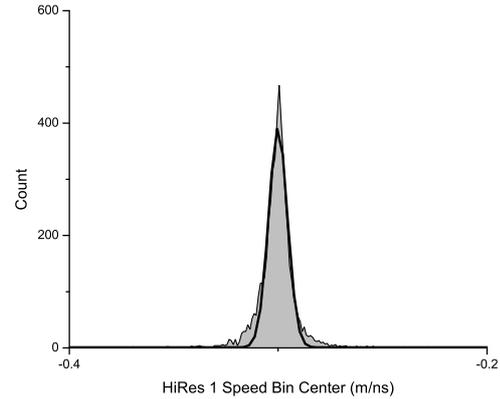


Fig. 5: Distribution from HiRes-1 Real Data

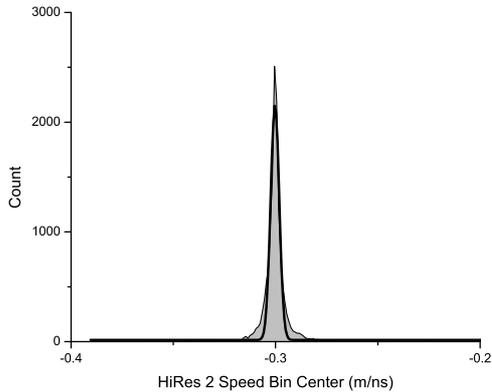


Fig. 4: Distribution from HiRes-2 Monte Carlo Data

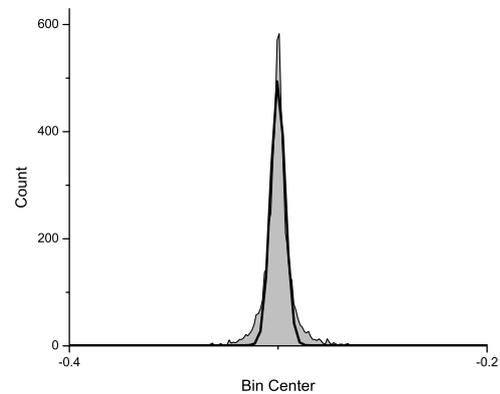


Fig. 6: Distribution from HiRes-2 Real Data

$$Cov(\sigma_{HR1}, \sigma_{HR2}) = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y}) \quad (3)$$

This cut was made post processing because the entire set of speeds was needed to calculate the covariance term between the two detectors.

With all cuts applied, 14,287 of the 53,452 Monte Carlo events remained in the sample. The resulting distributions are shown in Fig. 3 and Fig. 4. Of these, 106 events with speeds different more than three RMS from the speed of light were recorded.

These events were then subjected to a procedure which rotated the shower detector planes by small amounts until the reconstructed speed was equal to the speed of light. Two separate rotations were performed. The first was a rotation around an axis from the center of the detector to a weighted "center" of the observed event. This center was found by averaging the pointing directions of all phototubes weighted by the total integrated signal of each phototube. The second rotation corresponded to a rotation of the SDP around the center of the detector.

The resulting showers were analyzed to see if the new planes were consistent with the triggered tubes for each shower. Of the 106 events, 97 events were able to be adjusted to the speed of light while still maintaining

reasonable plane fits.

IV. REAL DATA

Once the procedure had been tested and verified on Monte Carlo Data, it was applied to the HiRes stereo data set. This consisted of data collected between December of 1999 and November of 2005. From this data, 5136 survived the cuts determined with Monte Carlo data. The resulting distributions are shown in Fig. 5 and Fig. 6.

Of these events, 10 had speeds that differed by more than 3 RMS from the speed of light. These 10 events were then subjected to the same rotation analysis described in the Monte Carlo section. In each case, the event was able to be matched to the speed of light while still consistent with pattern of tubes triggered.

Determining the statistical significance of this result requires the calculation of detector aperture.

V. PRELIMINARY CONCLUSIONS

No events were found in the HiRes data set with speeds significantly different from the speed of light. This is still a work in progress.

VI. ACKNOWLEDGEMENTS

This work is supported by US NSF grants PHY-9321949, PHY-9322298, PHY-9904048, PHY-9974537, PHY-0098826, PHY-0140688, PHY-0245428, PHY-0305516, PHY-0307098, and by the DOE grant FG0392ER40732. We gratefully acknowledge the contributions from the technical staffs of our home institutions. The cooperation of Colonels E. Fisher, G. Harter and G. Olsen, the US Army, and the Dugway Proving Ground staff is greatly appreciated.

REFERENCES

- [1] R. U. Abbasi *et al.*, Physical Review Letters 100, 101101 (2008).
- [2] W. F. Hanlon, in Physics (University of Utah, Salt Lake City, 2008), p. 333.
- [3] J. M. L. Jes Madsen, Physics Review Letters 90 (2003).