



Searching For Simultaneous Showers in the High Resolution Fly's Eye Data

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Abstract: A search was made for the interaction between cosmic rays and ions in the heliosphere using data collected by the High Resolution Fly's Eye's HiRes-1 detector. This interaction could produce a jet containing neutral pions which can lead to an observation of the unique signature of parallel, simultaneous photon showers. If observed, this would be suggestive of new physics affecting the propagation of extensive air showers. The results of this search are presented.

Keywords: HiRes, Heliosphere, Exotic

1 Cosmic Ray Interactions in the Heliosphere

Cosmic rays with energy $\gtrsim 10^{12}$ eV arrive at the Earth from sources far away from the Sun. As such, these particles must penetrate the Sun's heliosphere. Since the heliosphere is a plasma, an Ultra-High Energy Cosmic Ray (UHECR) can potentially interact with the ions within this plasma. If an UHECR proton interacts with the heliosphere, it will produce mostly pions. The charged pions will decay into muons and neutrinos, of which the muons will be subjected to magnetic bending. The neutral pions will decay into a pair of photons and will travel almost directly along the initial pion's trajectory. Once the photons reach the Earth they will act like ultra-high energy gamma rays with energies close to the initial pion which can be within one to two orders of magnitude of the primary cosmic ray. One dramatic difference, however, is that they will produce the unique signature of a pair of simultaneous, nearly parallel showers.

1.1 Cosmic Ray Interaction Probability

The heliosphere is created when supersonic particles expelled from the Sun interact with the supersonic particles of the intergalactic wind. The heliosphere is divided into different regions depending upon the speed and density of the particles creating it. The primary regions that can potentially produce an interaction with an UHECR are the termination shock, the heliosheath, and the hydrogen wall since they have the greatest density [1].

For an average energy of $\sim 10^{18.5}$ eV, the total cross-section is estimated to be approximately 120 mb from the HiRes experiment [2]. The inverse of the product of the

density of the region and the cross section gives the interaction length between a proton in the heliospheric plasma and the UHECR. The interaction probability is then determined by dividing the thickness of the region by the interaction length. The hydrogen wall is the region most likely to produce an interaction, but it is also the farthest away and will only interact with a $\sim 10^{-11}$ probability [1]. Due to this increasingly rare interaction, it is very unlikely to observe this kind of event, but this study was still performed to test whether one was observed.

1.2 Photon Observation

In the rest frame of the π^0 , the two photons would have trajectories directly away from each other in order to conserve momentum (see figure 1) and each would carry half of the mass energy of the pion, M_{π^0} . Four-vector, relativistic mechanics shows that the two photons would have a transverse direction which results in a trajectory away from the original direction of the pion which results in an opening angle between the two photons (see figure 1), and consequently a perpendicular separation

$$D_{\perp} = 2R \tan\left(\frac{|\theta_1| + |\theta_2|}{2}\right) \simeq R(|\theta_1| + |\theta_2|) \quad (1)$$

where θ is the lab-frame angle away from the pion's trajectory for photon i and R is the distance between the Earth and Heliosphere. Details of this calculation can be found in [1]. When the photons arrive at the Earth, the photons appear to have parallel trajectories, but with a transverse spread between the shower cores dependent upon the energy of the original pion and opening angle between the photons (see figure 2).

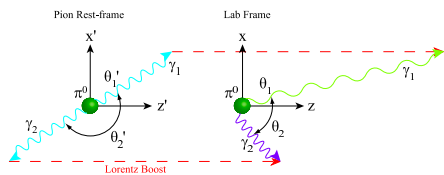


Figure 1: This figure shows the decay of a neutral pion in both its rest frame and the lab frame.

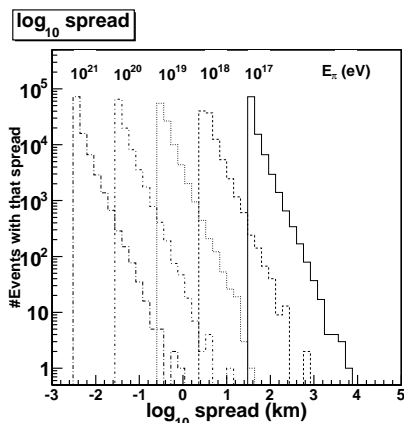


Figure 2: The perpendicular separation between Monte Carlo photons at various energies ($R = 75$ AU).

2 Searching for Double Showers

The High Resolution Fly's Eye HiRes-1 data was used for the study since it was the most extensive available at the time of this search. New techniques were developed in order to distinguish two separate showers within the data and Monte Carlo [1]. Primarily, the HiRes-1 Monte Carlo was modified to allow for two showers to be produced within a single event. Additionally a series of Hough transforms [3] were used to determine event shower tracks.

Depending upon the energy of the pion, and therefore the energy of and spread between the photon showers, the light produced in the extensive air shower can arrive at the detector in three different patterns: 1) within the same telescope within a single event, 2) in two separate telescopes within a single event, or 3) in two separate events. An event is defined as a $100 \mu\text{s}$ time window to combine information from separate telescopes observing the same shower.

2.1 Separate-Event Double Showers

The minimum time separation between the data events was determined to be $101 \mu\text{s}$, just above the time window between events. There is a strict dependance between the total photon energy ($E_{\pi^0} = \sum E_{\text{showers}}$), the energy difference ($\Delta E_{\text{showers}}$), and the time difference ($\Delta T_{\text{showers}}$) [1]. As such, the recorded event information is inconsistent with π^0 double-showers (see figure 3).

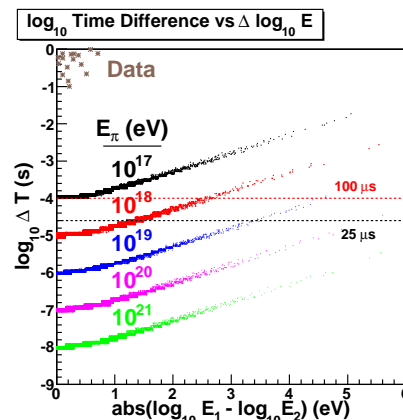


Figure 3: The difference in arrival time versus the difference in energy with observed event pairs. The Monte Carlo has predictable patterns which is inconsistent for the data.

2.2 Single-Event Double Showers

After removing all known laser events that showed to have two tracks within a single event, there were still 23 events that appeared to be double showers. In order to justify the removal of these events a test was made using the trigger time, t_i , and the in-plane angle, χ_i , to check if the two clusters could be from the same shower. To do this, a Hough transform was applied to the time-versus-angle (TvA) distribution to test the separation between the tracks.

There are three ways double-shower Monte Carlo was observed by the detector that affects the TvA and the corresponding Hough transform distributions. The first is a distinct double-shower pattern in the event display with the showers arriving at different times (see figure 4). The second pattern is where the two showers are approaching the detector in parallel and at the same time (see figure 5). The third is where the two showers completely overlap since their perpendicular separation is very narrow (see figure 6).

The primary question then becomes: how can these clusters be distinguished as separate shower tracks? To do this, a series Hough transform calculations were performed: 1) using individual, separate cluster Shower-Detector Planes (SDPs), 2) using the SDP of the first cluster for the second cluster, and 3) applying these processes to Monte Carlo events generated with only a single shower per event to determine precision cuts.

The calculation to determine the mean inclination angle, θ , and distance to the origin, r , first requires the metric of the two parameters to be the same. This is done by multiplying the angle of tube i in the SDP, χ_i , by the inverse angular speed, which has the units of $\mu\text{s}/\text{degree}$, to give χ'_i . The tube trigger time, t_i , is then plotted against χ'_i and time-ordered lines are determined between each pair of tubes (see figures 7 and 8). These lines are then used to calculate the correlated values of θ_i and r_i . Since the Hough lines can point between $(0^\circ, 180^\circ]$, there are many outlying points which need to be removed to determine a

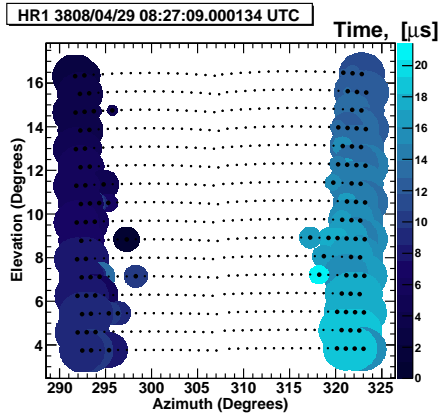


Figure 4: A Monte Carlo double-shower event with distinct time-trajectories as viewed by the detector.

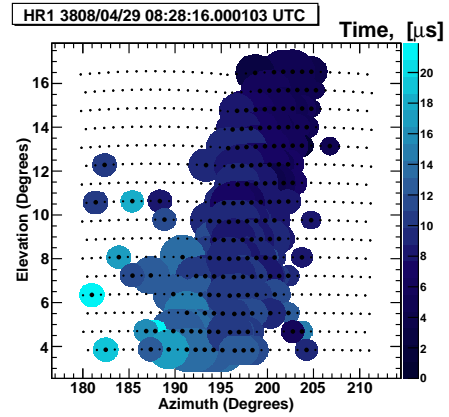


Figure 6: A Monte Carlo double-shower event with overlapping time-trajectories as viewed by the detector.

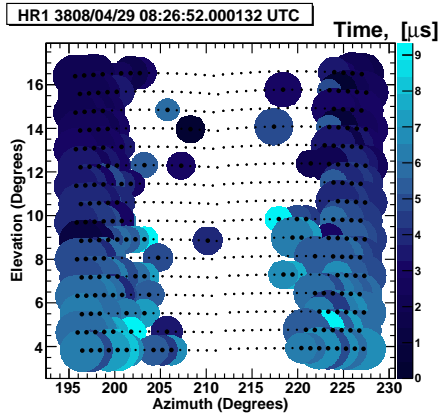


Figure 5: A Monte Carlo double-shower event with similar time-trajectories as viewed by the detector.

best-fit mean line. Each pair point is calculated to be some distance, \vec{X}_{jk} (the normalized RMS deviation), away from the mean, $|\vec{X}|$. Points $\vec{X}_{jk} \geq 2 \times |\vec{X}|$ are iteratively removed to determine a refined mean (see figure 9) [1].

The best way to determine if two lines could be considered the same track is to perform this same technique using the cluster-1 SDP to calculate the in-plane angle, χ , for both tracks (see figure 10). This shifts the χ_i of cluster 2, allowing for different \vec{X}_{jk} and $|\vec{X}|$ values to be determined. The distribution of the difference between \vec{X} determined using separate-versus-same SDPs for all Monte Carlo double-shower events was determined and compared to Monte Carlo events generated with single showers to determine “distinguishing” cuts (see figure 11). The 23 data events were then checked and it was determined that they were too close to the same track to claim the observation of double shower events (see figure 12).

2.3 Pion Decay Aperture

No double-shower events were observed by the HiRes-1 detector, so a flux for this form of interaction cannot be

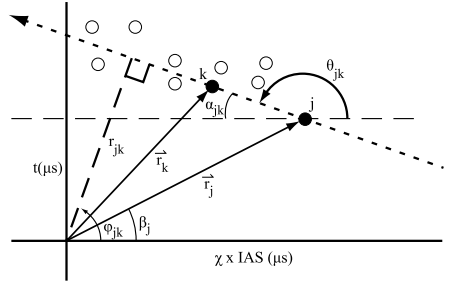


Figure 7: A schematic showing how a pair of TvA distribution points is converted into θ and r parameters using the Hough transformation.

measured. However, many events were able to be retained in the Monte Carlo, so a preliminary aperture can be determined (see figure 13). Future refinements of this study will be performed and result in an upper limit for this exotic interaction.

3 Acknowledgements

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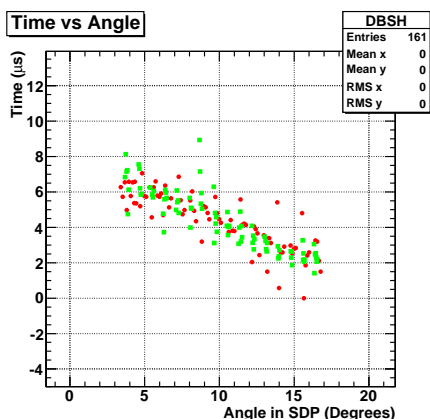


Figure 8: The individual-SDP TvA distribution of figure 5.

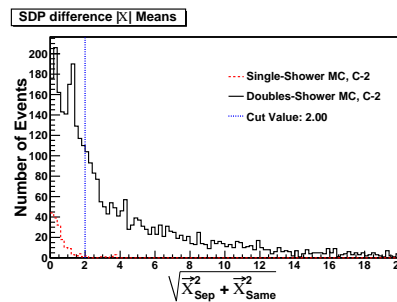


Figure 11: The distribution of the difference between $|\vec{X}|$ of cluster-2 using individual, separate SDPs and cluster-2 using the SDP of cluster 1 for double-shower Monte Carlo and single-shower Monte Carlo.

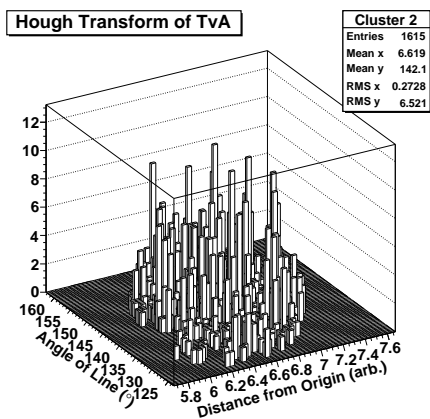


Figure 9: The d_{jk} and θ_{jk} distribution of cluster 2 of figure 8 using cluster 2's SDP; spurious points removed.

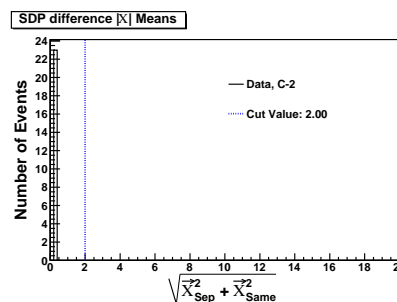


Figure 12: The distribution of the difference between $|\vec{X}|$ of cluster-2 using individual, separate SDPs and cluster-2 using the SDP of cluster 1 for data and single-shower Monte Carlo.

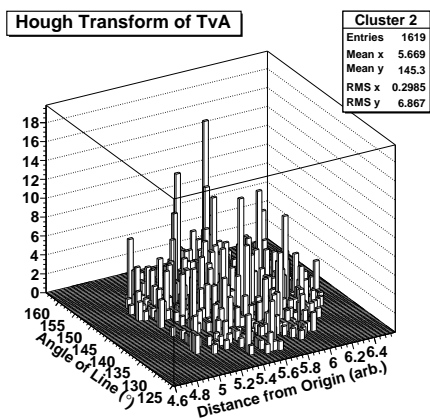


Figure 10: The d_{jk} and θ_{jk} distribution of cluster 2 of figure 8 using cluster 1's SDP; spurious points removed. Note the $|\vec{X}|$ value shifts by 2.5σ .

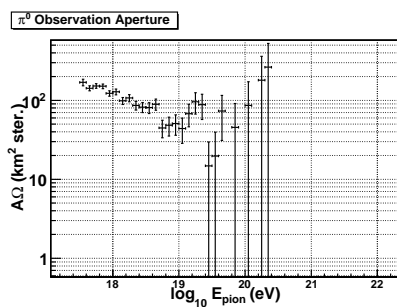


Figure 13: The true aperture of observing heliospheric π^0 decays calculated using the double-shower Monte Carlo.