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Search for correlations between HiRes stereo events and active galactic nuclei

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ABSTRACT

We have searched for correlations between the pointing directions of ultrahigh energy cosmic rays observed by the High Resolution Fly's Eye experiment and active galactic nuclei (AGN) visible from its northern hemisphere location. No correlations, other than random correlations, have been found. We report our results using search parameters prescribed by the Pierre Auger collaboration. Using these parameters, the Auger collaboration concludes that a positive correlation exists for sources visible to their southern hemisphere location. We also describe results using two methods for determining the chance probability of correlations: one in which a hypothesis is formed from scanning one half of the data and tested on the second half, and another which involves a scan over the entire data set. The most significant correlation found occurred with a chance probability of 24%.

1. Introduction

The search for the sources of the highest-energy cosmic rays is an important topic in physics today. The energies of these cosmic rays exceed 100 EeV and the acceleration mechanisms of the astrophysical objects responsible for these events remain unknown. Anisotropy search methods such as those used in X- or γ-ray astronomy are difficult to use due to deflections in the trajectories of these charged cosmic rays from galactic and extragalactic magnetic fields. For a galactic magnetic field strength of $\sim$3 μG and coherence length of $\sim$1 kpc, a 40 EeV cosmic ray should be deflected by two to three degrees over a distance of only a few kpc [1].

There are several reports on anisotropy by previous experiments. An excess of events near the direction of the galactic center has been reported by the SUGAR and AGASA experiments [2,3]. The Pierre Auger collaboration, however, has recently reported that they have not seen any excess at that location [4]. In addition, the Auger collaboration reported no significant excesses in any part of the southern hemisphere sky [5]. Two reports of anisotropy have been found in the northern hemisphere sky. A dip in the intensity of cosmic-ray events near the direction of the galactic anticenter has been reported by both the AGASA and High Resolution Fly's Eye (HiRes) experiments, but the significance is too low to claim an observation [6]. Additionally the AGASA "triplet" is correlated with a HiRes high-energy event [7]. These reports of anisotropy in the northern sky await confirmation or rejection by the Telescope Array experiment [8].

Another method for searching for anisotropy is to search for correlations in pointing directions of cosmic rays with known astrophysical objects that might be sources. In these cases, a small event sample that shows no excess over the expected background

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can, nevertheless, exhibit correlations with *a priori* candidate sources, adding up to a statistically significant signal. Past searches have found correlations with BL Lacertae objects; BL Lacs are a class of AGN with a jet pointing toward the Earth, and are plausible candidates for cosmic-ray sources. Correlations have been found with data from the AGASA, HiRes and Yakutsk experiments, all in the northern hemisphere [9]. The Auger collaboration has searched for correlations with BL Lac objects in the southern hemisphere but has found nothing significant [10]. Again the northern hemisphere correlations await confirmation by the Telescope Array experiment.

There have been speculations that active galactic nuclei (AGN) may contain acceleration regions of the appropriate size and magnetic field strength to accelerate nuclei to the highest energies [11,12]. One should therefore expect the brightest and closest AGN to produce the highest-energy cosmic-ray events at Earth. These events would also have suffered the smallest deflections due to the intervening magnetic fields and would point back, most directly, to these AGN. The large number of identified AGN make them interesting candidates for studying possible correlations with ultrahigh energy cosmic rays. Three ideal parameters for determining correlations between cosmic rays and AGN are the maximum difference in angle between the cosmic-ray pointing direction and the AGN θ_{max}, the minimum cosmic-ray energy E_{min}, and the maximum AGN redshift z_{max}.

The Pierre Auger Collaboration have reported a search of two independent sets of their data for correlations with cosmic rays with AGN. They scanned their first data set and found that the most significant correlation occurs for cosmic rays with parameters $(\theta_{max}, E_{min}, z_{max}) = (3.1°, 56\ \text{EeV}, 0.018)$. With these selection criteria, they find 12 pairings with AGN from 15 events in the first data set. In the second data set, they find 8 pairings from 13 events and a corresponding chance probability of 0.0017 [13,14].

The HiRes experiment collected data from 1997 to 2006, operating two fluorescence detectors located atop desert mountains separated by 12.6 km in west–central Utah. The HiRes data have been analyzed monocularly, using the data from one detector at a time [15], and stereoscopically, using the data from both detectors simultaneously [16]. The angular resolution is about 0.8° in stereo mode. The energy scales of the HiRes monocular and stereoscopic reconstructions agree. Only stereo data were used in this analysis. The stereo data, covering an energy range from $10^{17.4}$ to $10^{20.1}$ eV, consist of 6636 events.

The pointing directions of the stereo data extend from zenith to about −32° in declination (celestial coordinates). The corresponding exposure of is dependent on right ascension due to seasonal variations in the duty cycle of the detector. The boundaries of regions of equal exposure are best described by

$$\delta = \begin{cases} A + B\sin\left[\frac{9}{10}\alpha\right] & (\text{if } \alpha \leqslant 200°) \\ A + C\sin\left[\frac{9}{8}(\alpha - 200°)\right] & (\text{if } \alpha > 200°) \end{cases}, \quad (1)$$

where δ and α are celestial declination and right ascension measured in degrees and A, B and C are fit parameters. Table 1 gives values of A, B and C for plotting the boundaries of the 10 bins of equal exposure shown in Figs. 3 and 4.

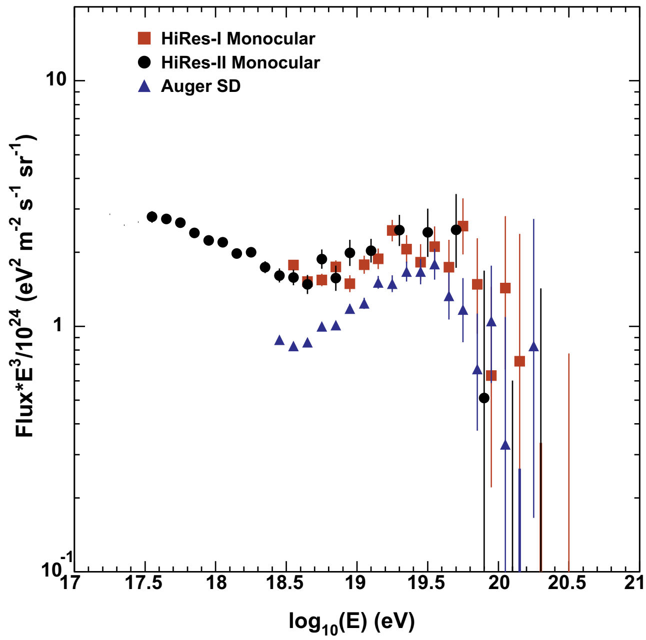

Fig. 1. Energy spectrum [E^3 J] for HiRes-1 and HiRes-2 monocular data [15] and for the surface detector data from the Pierre Auger Observatory [17].

Fig. 1 shows the monocular spectra for the two HiRes sites [15] and that of the Pierre Auger Observatory [17]. At the highest energies where Auger observes an anisotropy signal, the energy scales of HiRes and Auger differ by about 10%. To account for this difference, the energy scale of the HiRes stereo data set used in this analysis has been decreased by 10% to agree with the Auger energy scale. All energies quoted for the HiRes data from this point on will include this 10% shift. There are 13 events with energies greater than 56 EeV in the full HiRes stereo data set, the same number as in the Auger test data set.

2. The Véron-Cetty and Véron catalog

In this paper, we report on searches for correlations between the pointing directions of ultrahigh energy cosmic rays observed stereoscopically by the HiRes experiment and AGN from the Véron-Cetty and Véron (VCV) catalog, 12th edition [18]. The VCV catalog includes ∼22,000 AGN, ∼550 BL-Lacs and ∼85,000 quasars compiled from observations made by other scientists, and does not evenly cover the sky. Not only does the Galaxy and its associated dust cover large parts of the sky, particularly in the southern hemisphere, making the identification of AGN extremely difficult in those areas, but some of the sky surveys included in the catalog have covered only small bands of the sky. This makes the total density of AGN in the VCV catalog very uneven across the sky in a way that is neither totally random nor systematic. The locations of a closer subset of sources, with redshift $z < 0.1$, are more evenly distributed.

Table 1
Parameters for the functions in Eq. (1) that give the coordinates (in celestial right ascension and declination) of the lower boundaries of the 10 bins of equal exposure for the HiRes detector shown as the 10 lightest shaded regions in Figs. 3 and 4

Bin	1	2	3	4	5	6	7	8	9	10
A	67.9	55.3	45.5	36.9	28.8	20.7	12.3	3.3	−12.1	−32.0
B	2.0	3.0	3.8	4.7	5.5	6.6	7.9	9.4	17.6	0.0
C	−3.1	−4.4	−5.6	−7.0	−8.8	−11.5	−15.7	−26.2	−19.1	0.0

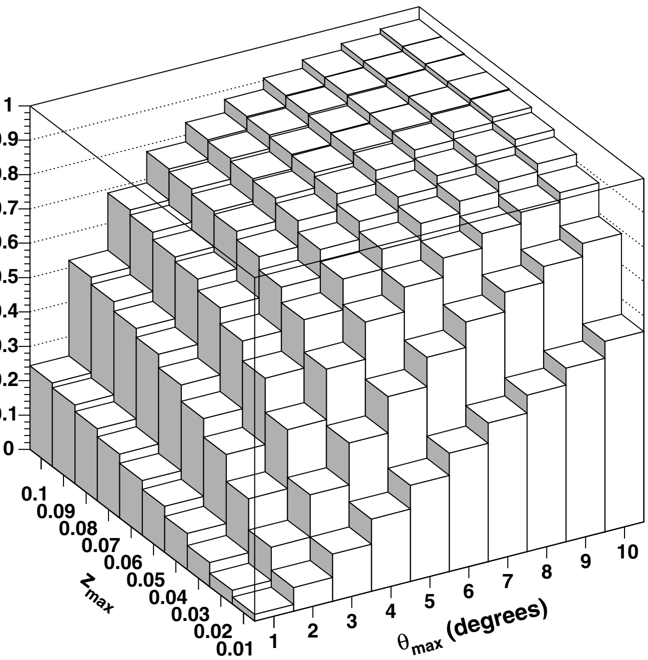

Fig. 2. The average fraction of correlated events found in 5000 simulated sets of isotropic events with identical statistics to the HiRes data for $E > 56$ EeV as a function of θ_{max} and z_{max}. The fraction of correlated pairs of simulated events with AGN is 0.02 at (1.0°, 0.010); 96% of events are correlated at (10.0°, 0.100).

One property of the search method in $(\theta_{max}, E_{min}, z_{max})$ is that the large size of the catalog and the size of the correlation angle circles determine that one can scan over only a narrow range of θ_{max} and z_{max}. To illustrate this using simulated events with isotropically distributed pointing directions, Fig. 2 shows that the number of random pairings with AGN is determined by the choice of θ_{max} and z_{max}. As θ_{max} and z_{max} are increased, the number of random pairings increases, rapidly overcoming any real correlations between cosmic rays and AGN.

3. Method

We perform three searches for correlations between cosmic rays and AGN. In the first search we look for correlations in the HiRes stereo data using the $(\theta_{max}, E_{min}, z_{max})$ parameters prescribed by the Auger collaboration [13]. In the second, we divide our stereo data into two equal parts in a random manner, determine the optimum search parameters in the first half of the data by scanning in a three-dimensional grid in $(\theta_{max}, E_{min}, z_{max})$, and then examine the second half of the data using these "optimum" parameters. By choosing the best parameters from the first half of the data and using them to form a hypothesis to be tested using a statistically independent sample, no statistical penalties are incurred in the application to the second half of the data. In the third and last search, we analyzed the complete data set using the statistical prescription described by Finley and Westerhoff [19] (see also Tinyakov and Tkachev [20]) to arrive at a chance probability that includes the statistical penalty from scanning over the entire data set. Finally, in addition to searching for correlations with AGN, we analyzed the degree of auto-correlation in the stereo data over all possible angles and values of E_{min}.

To arrive at the appropriate chance probabilities for the numbers of correlations seen in each method, we generated 5001 random samples of events using the hour angle-declination method [21,6]. In this method, the hour angle and declination of one event and the sidereal time of another are randomly paired to generate a sky plot with the same number of events as the data. Such a sample reproduces the overall observed distribution of events very well.

3.1. Search for correlations using the Auger criteria

The Auger collaboration has reported the results of searches in $(\theta_{max}, E_{min}, z_{max})$ over two independent data sets. In a scan over the first data set, 12 of the 15 events with $E_{min} = 56.0$ EeV were found to lie within $\theta_{max} = 3.1°$ of AGN with $z_{max} = 0.018$ with 3.2 chance pairings expected. Using the parameters (3.1°, 56.0 EeV, 0.018), 8 of 13 events in an independent test data set were found to be paired with AGN with 2.7 chance pairings expected. The chance probability for this occurrence was found to be 0.0017 [13,14].

A scan of the entire HiRes data set at (3.1°, 56.0 EeV, 0.018) found 2 AGN pairings for a total of 13 events. Fig. 3 shows the locations of the 2 correlated events and the 11 uncorrelated events. We looked for correlations in the 5000 simulated data sets at (3.1°, 56.0 EeV, 0.018) and found the average number of correlated pairs to be 3.2. In addition, 4121 sets had 2 or more correlated events for a chance probability of 82%. We thus find no evidence for correlations of cosmic-ray events with AGN in our field of view at (3.1°, 56.0 EeV, 0.018). The HiRes data are therefore consistent with random correlations.

3.2. Search in two independent data sets

Next, we randomly divide the HiRes stereo data into two equal sets, first examining only one half and setting the other aside. We

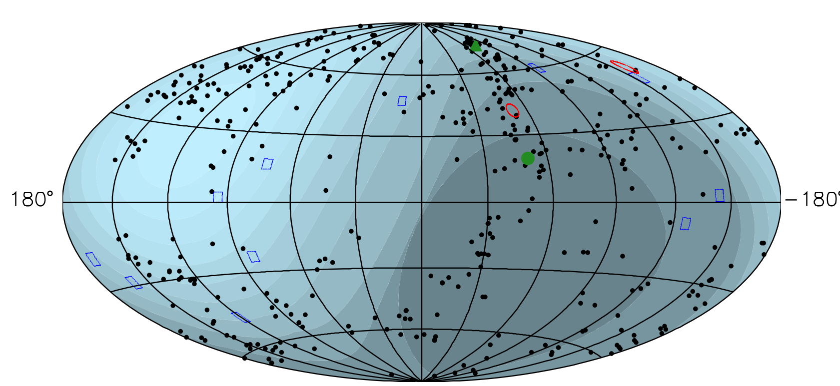

Fig. 3. Sky map in galactic coordinates. The black dots are the locations of the 457 AGN and 14 QSOs with redshift $z < 0.018$. The green circle and triangle mark the locations of Centaurus A and M87, respectively. The red circles (with radii of 3.1°) mark the 2 correlated events. The blue squares mark the locations of the 11 uncorrelated events. Of the eleven blue shaded regions, the 10 lightest shades delineate regions of constant exposure in HiRes as given in Table 1. The darkest shade indicates the region with no exposure. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

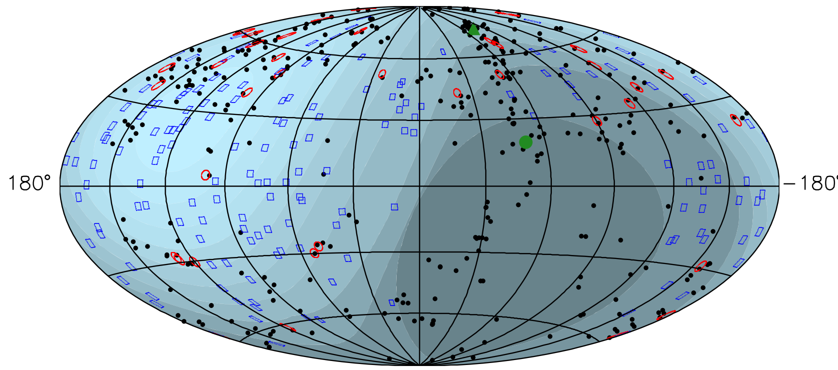

Fig. 4. Sky map in galactic coordinates. The black dots are the locations of the 389 AGN and 14 QSOs with redshift $z < 0.016$. The green circle and triangle mark the locations of Centaurus A and M87, respectively. The red circles (with radii of 2.0°) mark the 36 correlated events at (2.0°, 15.8 EeV, 0.016). The blue squares mark the locations of the 162 uncorrelated events. Of the eleven blue shaded regions, the 10 lightest shades delineate regions of constant exposure in HiRes as given in Table 1. The darkest shade indicates the region with no exposure. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

scan the first half simultaneously in θ_{max} from 0.1 to 4.0° in bins of 0.1°, in E_{min} from $10^{19.05}$ to $10^{19.80}$ eV in bins of 0.05 decade, and with an AGN z_{max} from 0.010 to 0.030 in bins of 0.001. For each grid point in the scan, the total number of cosmic rays correlated with at least one AGN is accumulated. We then conduct the same scan in each of 5000 simulated sets with identical statistics to the first half, adding up the total number of correlations in each set for each grid point. At each point, the number of correlated events in each of the 5000 simulated sets is compared with the result in the first half of the data. The criteria for the most significant correlation were found to be (1.7°, 15.8 EeV, 0.020) with 20 correlated events from a total of 97. Only 25 of 5000 simulated sets had 20 or more correlations.

Using these criteria as our hypothesis, we then examine the second half of the data at (1.7°, 15.8 EeV, 0.020) and find 14 correlated pairs from 101 events. In a set of 5000 simulated events with identical statistics to the second half, 741 sets contained 14 or more correlated events for a chance probability of 15%. For comparison, the point with the most significant correlation in the second half occurs at (2.0°, 20.0 EeV, 0.016) with 14 correlated events of a total 69 and a chance probability of 1.5%. These results are again consistent with random correlations.

3.3. Scanning the entire data set

We follow the prescription of Finley and Westerhoff [19] for determining the most significant correlation in the entire data set while also calculating an appropriate statistical penalty for scanning over the entire data set. We scan the data simultaneously in θ_{max}, E_{min} and z_{max} counting the number of correlated events, n_{corr}

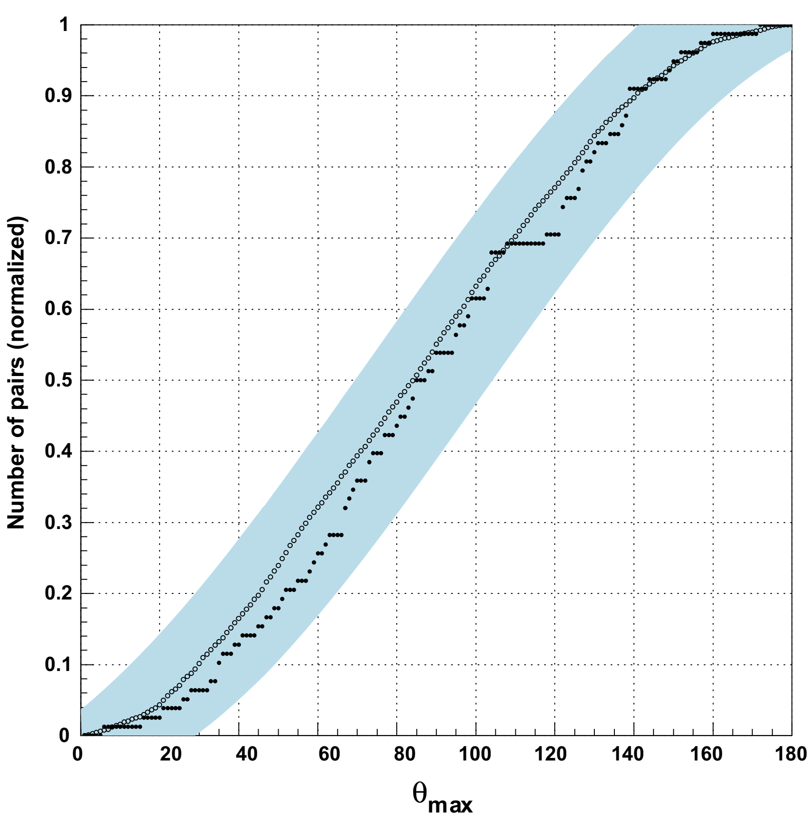

Fig. 5. Normalized number of pairs as a function of θ_{max}. The 13 events above 56 EeV in the HiRes data are shown in closed circles. The open circles are the average of 2000 simulated sets. The gray shaded region represents the 1σ uncertainty in the distribution of simulated sets.

at each point. This process is repeated for each of the 5001 simulated sets with P_{data}, the probability for observing n_{corr} or more correlations at $(\theta_{max}, E_{min}, z_{max})$ calculated from

$$P_{data}(\theta_{max}, z_{max}, E_{min}) = \sum_{n=n_{corr}}^{\infty} P_{mc}(\theta_{max}, z_{max}, E_{min}, n), \quad (2)$$

where $P_{mc}(\theta_{max}, z_{max}, E_{min}, n)$ is the fraction of the first 5000 simulated sets with exactly n events at $(\theta_{max}, E_{min}, z_{max})$. The value of P_{min} is then taken to be the values of (θ_c, E_c, z_c) which minimize P_{data}. This is found to occur at the critical values (2.0°, 15.8 EeV, 0.016) where there are 36 correlated events out of 198 in the data and 9 of 5000 simulated sets with 36 or more correlated events, for a chance probability of 0.18%.

To find the true significance of this signal, we apply the same process to each of the first 5000 simulated sets, finding the value $P^i_{min} = P^i(\theta^i_c, E^i_c, z^i_c)$ by comparing n^i_{corr} with n_{corr} for the other 5000 sets. We then count the number of simulated sets n^*_{mc} for which $P^i_{min} \leqslant P_{min}$. The chance probability is then found as

$$P_{chance} = \frac{n^*_{mc}}{5000}. \quad (3)$$

In this, our most robust method, there were 1210 simulated sets with P^i_{min} values of 0.0018 or less for a chance probability, $P_{chance} = 24\%$. Fig. 4 shows a sky map of the most significant correlation in the HiRes data. From this final analysis, we draw the same conclusion: HiRes data are consistent with random correlations with AGN.

4. Auto-correlation analysis

In addition to searching for correlations with AGN, studies of auto-correlation can be useful for searching for anisotropy in the data. We have analyzed the degree of auto-correlation in the data over all possible angles and made comparisons with the average number of pairs of events for 2000 isotropic simulated data sets. We find no evidence of auto-correlation for any values of E_{min}. Fig. 5 shows a comparison of the normalized number of pairs of events with energies above 56 EeV in the stereo data to the average normalized number of pairs for 2000 isotropic simulated data sets. The 1σ uncertainty is found by ordering the simulated sets by their maximum deviation from the average and plotting only the first 68% of those simulated sets.

As a further check, we scan the data in θ_{max} and E_{min} and determine a statistical penalty using the same method presented in Section 3.3. We scan the data in θ_{max} from 0.5° to 30.0° in bins of 0.5° and in E_{min} from $10^{19.05}$ to $10^{19.80}$ eV in bins of 0.05 decade. The critical values which minimize P_{data} are found to occur at (2.0°, 44.7 EeV) where there is one pair of events out of a possible 406 in the data and 227 of 1000 simulated sets with one or more pairs for a chance probability of 23%. Applying the same process to the 1000 simulated sets, we find 971 sets for which the critical point occurs with a chance probability less than 23%. The probability of measuring the observed degree of correlation in an isotropic data set is 97%.

5. Conclusions

We have searched for correlations between the pointing directions of HiRes stereo events with AGN from the the Véron-Cetty Véron catalog using three different methods. As search parameters for our analysis, we used the maximum difference in angle between the cosmic-ray pointing direction and an AGN θ_{max}, the minimum cosmic-ray energy E_{min}, and the maximum AGN redshift z_{max}.

Our first analysis, using the criteria prescribed by the Pierre Auger Observatory for their most significant correlation, (3.1°, 56.0 EeV, 0.018), finds 2 correlated of 13 total events with an expectation of 3.2 chance correlations. The corresponding chance probability was found to be 82%.

In our second search the total HiRes stereo data were then divided into two equal but random parts and we performed a scan in θ_{max}, E_{min} and z_{max} over one half of the data to determine which parameters optimized the correlation signal. We then examined the other half of the data using these search parameters and found a smaller signal with a chance probability of 15%.

Finally, we examined the entire HiRes stereo data using a more robust method to calculate the chance probability with appropriate statistical penalties. The most significant correlation was found to occur at (2.0°, 15.8 EeV, 0.016) with 36 correlated of 198 total events. This corresponds to a chance probability of 24%.

We conclude that there are no significant correlations between the HiRes stereo data and the AGN in the Véron-Cetty Véron catalog. We also examined the degree of auto-correlation at all angles and energies. The probability that the data are consistent with isotropy is 97%.

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