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SEARCH FOR CROSS-CORRELATIONS OF ULTRAHIGH-ENERGY COSMIC RAYS WITH BL LACERTAE OBJECTS

R. U. Abbasi,[1] T. Abu-Zayyad,[1] J. F. Amann,[2] G. Archbold,[1] K. Belov,[1] J. W. Belz,[3] S. BenZvi,[4] D. R. Bergman,[5]
S. A. Blake,[1] J. H. Boyer,[4] G. W. Burt,[1] Z. Cao,[1] B. M. Connolly,[4] W. Deng,[1] Y. Fedorova,[1] J. Findlay,[1]
C. B. Finley,[4] W. F. Hanlon,[1] C. M. Hoffman,[2] M. H. Holzscheiter,[2] G. A. Hughes,[5] P. Hüntemeyer,[1]
C. C. H. Jui,[1] K. Kim,[1] M. A. Kirn,[3] B. C. Knapp,[4] E. C. Loh,[1] M. M. Maestas,[1] N. Manago,[6]
E. J. Mannel,[4] L. J. Marek,[2] K. Martens,[1] J. A. J. Matthews,[7] J. N. Matthews,[1] A. O'Neill,[4]
C. A. Painter,[2] L. Perera,[5] K. Reil,[1] R. Riehle,[1] M. D. Roberts,[7] D. Rodriguez,[1]
M. Sasaki,[6] S. R. Schnetzer,[5] M. Seman,[4] G. Sinnis,[2] J. D. Smith,[1] R. Snow,[1]
P. Sokolsky,[1] R. W. Springer,[1] B. T. Stokes,[1] J. R. Thomas,[1] S. B. Thomas,[1]
G. B. Thomson,[5] D. Tupa,[2] S. Westerhoff,[4] L. R. Wiencke,[1] and A. Zech[5]
(The HiRes Collaboration)

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ABSTRACT

Data taken in stereo mode by the High Resolution Fly's Eye (HiRes) air fluorescence experiment are analyzed to search for correlations between the arrival directions of ultrahigh-energy cosmic rays with the positions of BL Lacertae objects. Several previous claims of significant correlations between BL Lac objects and cosmic rays observed by other experiments are tested. These claims are not supported by the HiRes data. However, we verify a recent analysis of correlations between HiRes events and a subset of confirmed BL Lac objects from the 10th Veron Catalog, and we study this correlation in detail. Due to the a posteriori nature of the search, the significance level cannot be reliably estimated and the correlation must be tested independently before any claim can be made. We identify the precise hypotheses that will be tested with statistically independent data.

Subject headings: BL Lacertae objects: general — cosmic rays — galaxies: active

1. INTRODUCTION

Among the most striking astrophysical phenomena today is the existence of cosmic-ray particles with energies up to and exceeding 10^{20} eV. It is currently unknown where and how these particles are accelerated to such energies and how they travel astronomical distances without substantial energy loss.

In an attempt to understand the origin of these particles, the limited world data set of ultrahigh-energy cosmic-ray arrival directions has been subjected to extensive searches for correlations with the positions of objects from known astrophysical source classes. In particular, significant correlations between subsets of BL Lacertae objects and cosmic-ray arrival directions recorded by the Akeno Giant Air Shower Array (AGASA) and the Yakutsk experiment have been claimed (Tinyakov & Tkachev 2001, 2002; Gorbunov et al. 2002). Searches for correlations with BL Lac objects are well motivated. BL Lac objects are a subclass of blazars, which are active galaxies in which the jet axis happens to point almost directly along the line of sight. The EGRET instrument on board the *Compton Gamma Ray Observatory* (*CGRO*) has firmly established blazars as sources of high energy γ-rays above 100 MeV (Hartman et al. 1999), and several BL Lac objects have been observed at TeV energies with ground-based air Cerenkov telescopes (see Horan & Weekes 2004 for a summary). High energy γ-rays could be by-products of electromagnetic cascades from energy losses associated with the acceleration of ultrahigh-energy cosmic rays and their propagation in intergalactic space (Berezinskii et al. 1990; Coppi & Aharonian 1997).

However, the claimed correlations between ultrahigh-energy cosmic-ray arrival directions and BL Lac objects are controversial. A problematic aspect of the claims is the procedure used to establish correlations and evaluate their statistical significance. Several authors (Tinyakov & Tkachev 2001, 2002; Gorbunov et al. 2002) explicitly tuned their selection criteria to assemble catalogs that show a maximum correlation with arrival directions of cosmic rays above some energy. An unbiased chance probability for these correlations can then only be arrived at if the claim is tested on a statistically independent data set. Since the available data set is small, this rigorous procedure is often abandoned, and instead an attempt is made to estimate a statistical penalty factor to compensate for the number of trials involved in the tuning. "Hidden" trials, unfortunately, make these a posteriori estimates highly unreliable, and claims of BL Lac correlations have been criticized on these grounds (Evans et al. 2003; Stern & Poutanen 2005). It has also been shown in some cases that statistically independent data sets do not confirm the correlations (Torres et al. 2003).

The operation of the stereoscopic HiRes air fluorescence detector is providing a large data set of cosmic-ray events with unprecedented angular resolution for the study of small-scale anisotropy and source correlations. In this paper, we report on searches for correlations between BL Lac objects and HiRes stereoscopic events observed between 1999 December and 2004 January. The quality cuts applied to this data sample are described in detail in Abbasi et al. (2004, 2005b).

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[1] Department of Physics and High Energy Astrophysics Institute, University of Utah, Salt Lake City, UT 84112.
[2] Los Alamos National Laboratory, Los Alamos, NM 87545.
[3] Department of Physics and Astronomy, University of Montana, Missoula, MT 59812.
[4] Department of Physics and Nevis Laboratories, Columbia University, New York, NY 10027; finley@physics.columbia.edu, westerhoff@nevis.columbia.edu.
[5] Department of Physics and Astronomy, Rutgers, the State University of New Jersey, Piscataway, NJ 08854.
[6] Institute for Cosmic Ray Research, University of Tokyo, Kashiwa City, Chiba 277-8582, Japan.
[7] Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131.

The outline of the paper is as follows. In § 2, we describe our use of the maximum likelihood method for correlation searches with multiple sources. In § 3, we consider the previous claims of correlations between BL Lac objects and ultrahigh-energy cosmic rays and test them using HiRes stereo data. In § 4, we perform a general search for correlations between the HiRes data set and confirmed BL Lac objects. In § 5, we summarize the results and discuss further studies.

2. MAXIMUM LIKELIHOOD METHOD

2.1. *Description*

To address a number of shortcomings of binned analyses of cosmic-ray arrival directions, we have recently applied an *unbinned* maximum likelihood method in the search for point sources of ultrahigh-energy cosmic rays (Abbasi et al. 2005b). This approach uses the probability density function for each individual event rather than requiring a fixed bin size. Two important advantages of this method are the ability to accommodate events with different errors and to give weighted sensitivity to angular separations, avoiding the loss of information that follows from choosing an angular separation cutoff. With minor modifications, the same maximum likelihood method can also be used to search for correlations with a specified list of potential sources.

The premise involved in the maximum likelihood analysis is that the data sample of N events consists of n_s source events that came from some source position(s) in the sky, and $N - n_s$ background events. A background event arrives according to the probability distribution given by the detector exposure to the sky, $R(\boldsymbol{x})$, where $\boldsymbol{x}$ are equatorial coordinates. The true arrival direction of a source event is the location of the source $\boldsymbol{s}$, but the event is observed somewhere near $\boldsymbol{s}$ according to the probability distribution $Q_i(\boldsymbol{x}, \boldsymbol{s})$, where Q_i depends on the angular uncertainty in arrival direction of the ith event.

Because it is not known whether a given event is a source or background event, the probability distribution function (or "partial" probability) for the ith event is a weighted sum of the source and background probability distributions,

$$P_i(\boldsymbol{x}) = \frac{n_s}{N} Q_i(\boldsymbol{x},\ \boldsymbol{s}) + \frac{N - n_s}{N} R(\boldsymbol{x}). \qquad (1)$$

This describes the distribution of arrival directions under a single-source hypothesis. For a hypothesis with M sources, we must modify Q to include multiple source locations. We assume for this analysis that the sources have equal luminosity. In this case, we only need to compensate for the varying exposure of the detector to different parts of the sky: the probability for a source event to come from the jth source is proportional to the detector exposure $R(\boldsymbol{s}_j)$ to the source location $\boldsymbol{s}_j$. The total source probability distribution $Q_i^{\rm tot}$ for the ith event is then the weighted sum of the individual source probabilities:

$$Q_i^{\rm tot}(\boldsymbol{x}) = \sum_{j=1}^{M} R(\boldsymbol{s}_j) Q_i(\boldsymbol{x},\ \boldsymbol{s}_j) \times \left[\sum_{k=1}^{M} R(\boldsymbol{s}_k)\right]^{-1}. \qquad (2)$$

Replacing Q_i in equation (1) with $Q_i^{\rm tot}$, we evaluate the partial probability of the ith event at its observed location $\boldsymbol{x}_i$,

$$P_i(\boldsymbol{x}_i) = \frac{n_s}{N} Q_i^{\rm tot}(\boldsymbol{x}_i) + \frac{N - n_s}{N} R(\boldsymbol{x}_i). \qquad (3)$$

The likelihood for the entire set of N events is then given by

$$\mathcal{L}(n_s) = \prod_{i=1}^{N} P_i(\boldsymbol{x}_i). \qquad (4)$$

The best estimate for the number of events contributed by the sources is determined by finding the value of n_s that maximizes $\mathcal{L}$.

Because the value of the likelihood function depends on the number of events, a more useful quantity than $\mathcal{L}$ is the likelihood ratio $\mathcal{R}$,

$$\mathcal{R}(n_s) = \frac{\mathcal{L}(n_s)}{\mathcal{L}(0)} = \prod_{i=1}^{N} \left[\frac{n_s}{N}\left(\frac{Q_i^{\rm tot}(\boldsymbol{x}_i)}{R(\boldsymbol{x}_i)} - 1\right) + 1\right],$$

where $\mathcal{L}(0)$ is the likelihood function of the null hypothesis ($n_s = 0$). In practice, we maximize $\ln \mathcal{R}$, which is equivalent to maximizing $\mathcal{L}$.

The significance of the resulting $\ln \mathcal{R}$ can be estimated using $\chi^2 = 2 \ln \mathcal{R}$. When n_s is positive, this agrees well with the χ^2 distribution for 1 degree of freedom. Because n_s corresponds to the *excess* number of events correlating with source positions, a negative best-fit value for n_s will occur whenever there are fewer events near source positions than expected. Negative n_s values are not physically meaningful in the point-source search, but they are useful for evaluating significances. To distinguish an excess in correlations from a deficit, we assign the negative solution $\chi = -(2 \ln \mathcal{R})^{1/2}$ when the best-fit n_s is negative. We can then check the significance estimated from the χ^2 distribution by performing the same likelihood analysis on simulated data sets and ranking them according to their χ values. We will use $\mathcal{F}$ to denote the fraction of simulated, isotropic event sets which yield a value of χ greater than or equal to that of the data.

2.2. *Implementation*

For the source probability function Q_i we employ a circular Gaussian of width σ_i corresponding to the angular uncertainty of the ith event, as estimated by the stereo event reconstruction. The mean of the angular uncertainty of the HiRes stereo events is slightly larger at lower energies, growing from $\langle\sigma\rangle = 0\overset{\circ}{.}44$ above 10^{18} eV to $\langle\sigma\rangle = 0\overset{\circ}{.}60$ below $10^{17.75}$ eV. This, of course, is accounted for by the use of individual errors in the maximum likelihood analysis.

Because the geometrical acceptance of the detector is a function of energy, we determine the background probability distribution $R(\boldsymbol{x})$ in two different ways. For large event samples ($\gtrsim 1000$), we generate a background distribution from a full time-swapping of the data itself; the equatorial coordinates of each event are recalculated using all of the recorded event times, and $R(\boldsymbol{x})$ is the cumulative map of all of these virtual event locations convolved with a circular Gaussian function for smoothing. For small event samples (e.g., the 271 events above 10^{19} eV) the data set is too sparse to generate a useful time-swapped map. Instead, we rely on a full detector simulation to estimate the local geometrical acceptance, and convolve this with the event times to generate $R(\boldsymbol{x})$. This procedure and the detector simulation are described in more detail in Abbasi et al. (2004).

3. TESTS OF PREVIOUS CORRELATIONS OBSERVED WITH AGASA AND YAKUTSK DATA

We briefly review some past claims of correlations between cosmic-ray arrival directions and BL Lac objects, and then test these with HiRes data under the same conditions. All samples of BL Lac objects are selected from objects classified as "BL" in

TABLE 1

Previously Claimed Correlations Between BL Lac objects and Cosmic Rays, and Tests with Independent HiRes Data

Claim and Test	Sample (No. Objects)	References	CR Data and Energy Threshold (EeV)	No. of Events	Binned Analysis			Maximum Likelihood Analysis		
					Bin Size (deg)	Pairs	Prob.	$\ln \mathcal{R}$	n_s	$\mathcal{F}$
Claim 1	A (22)	TT01	AGASA > 48, Yak. > 24	65	2.5	8	$<10^{-4}$			
Test			HiRes > 24	66	2.5	0	1.00	(0)	(0)	0.75
Claim 2	B (157)	TT02	AGASA > 40	57	2.5	12	0.02			
Test			HiRes > 40	27	2.5	2	0.78	(0)	(0)	0.26
Claim 3	C (14)	G02	AGASA > 48, Yak. > 24	65	2.9	8	10^{-4}			
Test			HiRes > 24	66	2.9	1	0.70	(0)	(0)	0.68

References.—(G02) Gorbunov et al. 2002; (TT01) Tinyakov & Tkachev 2001; (TT02) Tinyakov & Tkachev 2002. In TT02 and G02, the authors also attempt to correct for the deflections of charged primaries by the galactic magnetic field; these results are not considered here.

Table 2 of the Veron Catalog of Quasars and AGN (9th or 10th editions; Veron-Cetty & Veron 2000, 2001).

1. Sample A, described in Tinyakov & Tkachev (2001), contains 22 BL Lac objects from the Veron 9th Catalog, selected on the basis of optical magnitude ($m < 18$), redshift ($z > 0.1$ or unknown), and 6 cm radio flux ($F_6 > 0.17$ Jy).
2. Sample B, described in Tinyakov & Tkachev (2002), contains 157 BL Lac objects from the Veron 10th Catalog with optical magnitude $m < 18$.
3. Sample C, described in Gorbunov et al. (2002), consists of 14 BL Lac objects from the Veron 10th catalog that were selected by the authors on the basis of possible association with identified and unidentified γ-ray sources in the Third EGRET Catalog (Hartman et al. 1999).

Table 1 shows the correlations originally claimed using these BL Lac samples and cosmic-ray data from the AGASA and Yakutsk experiments. The energy thresholds and angular bin sizes vary from analysis to analysis as shown. The results of testing each claim as nearly as possible with an equivalent set of HiRes data are also presented. Both a binned analysis with the bin size originally used and a maximum likelihood analysis using the point-spread function of individual HiRes events are performed. In the binned analysis, the number of event-object pairs with angular separation less than the bin size are counted, and the probability for the same or a greater number of pairs is evaluated using simulated isotropic event sets. None of the three previous claims of correlations based on other cosmic-ray data sets are confirmed by the tests. Each test, in fact, finds a deficit or no excess of HiRes events correlating with BL Lac objects, indicated by (0) values for $\ln \mathcal{R}$ and n_s. The fraction $\mathcal{F}$ of simulated sets with stronger correlation than the data is calculated as described above.

In the tests of claims 1 and 3, the size of the HiRes event sample is comparable to the size of the combined AGASA and Yakutsk event samples. Assuming a Poisson distribution with the mean number of event-BL Lac pairs given by the AGASA and Yakutsk results, the observed number of HiRes-BL Lac pairs excludes the claimed correlations at a confidence level greater than 99% in each case. In the test of claim 2, the HiRes event sample is smaller than that of AGASA. Here the claimed correlation is excluded at the 90% confidence level.

4. RECENT CORRELATIONS OBSERVED WITH HiRes DATA

Recently, the published HiRes events above 10^{19} eV were analyzed by Gorbunov et al. (2004), and correlations with the BL Lac objects of Sample B were claimed at the 10^{-3} level. The analysis used a fixed bin size of $0\overset{\circ}{.}8$, which the authors argued is optimal for a point-source search given the HiRes angular resolution. (See e.g., Alexandreas et al. [1992], which describes a direct calculation of the optimal bin size that agrees with this value.) We verify this analysis by applying the maximum likelihood method to the same data set and source sample, and find $\ln \mathcal{R} = 6.08$ for $n_s = 8.0$; the fraction of Monte Carlo sets with higher $\ln \mathcal{R}$ is $\mathcal{F} = 2 \times 10^{-4}$.

Gorbunov et al. (2004) analyzed the entire set of HiRes events above 10^{19} eV because the individual event energies were not published. Therefore this energy threshold was not tuned to maximize correlations with BL Lac objects. However, because the original claim (Tinyakov & Tkachev 2002) was based on AGASA data with energies above 4×10^{19} eV, the correlation in Gorbunov et al. (2004) does not confirm a previous claim, but rather represents a new hypothesis. This is demonstrated by the fact that the HiRes data show no excess correlation with this sample of BL Lac objects when the same 4×10^{19} eV energy threshold is used, as indicated in the test of claim 2 in Table 1.

The observed correlation warrants further investigation. We report on extending the analysis to lower energy HiRes data and to the rest of the confirmed BL Lac objects in the Veron catalog.

4.1. *Event Sample: Energy Dependence of Correlations*

An important question is whether and how the observed correlation depends on the energy threshold. Figure 1 shows the result of the same maximum likelihood analysis above, performed repeatedly using increasing energy thresholds from $10^{18.5}$ to 10^{20} eV. The 10^{19} eV threshold corresponding to the published data set is indicated, and it clearly stands out as the threshold that gives a local maximum in the significance of the correlation.

One of the motivations for using an energy threshold in small-scale anisotropy searches is that charged cosmic-ray primaries

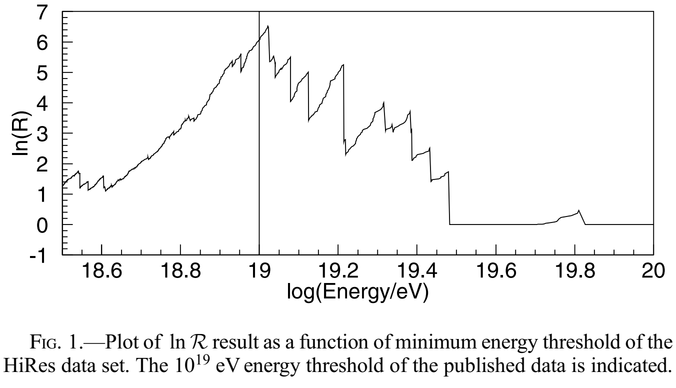

Fig. 1.—Plot of $\ln \mathcal{R}$ result as a function of minimum energy threshold of the HiRes data set. The 10^{19} eV energy threshold of the published data is indicated.

are subject to deflection by galactic and extragalactic magnetic fields. The highest energy primaries will be least deflected, and consequently will be the best candidates for correlation studies. However, an a priori energy threshold cannot be established, because detailed knowledge of the galactic and extragalactic magnetic fields is lacking.

Figure 1 indicates that most of the correlation comes from events with energies between 10^{19} and $10^{19.5}$ eV. At these energies, it is generally assumed that the Galactic magnetic field will deflect a proton primary by many degrees; nuclei will be deflected even more. In spite of this, the correlations are consistent with the $\sim 0^{\circ}.5$ scale of the detector angular resolution. This might imply that the correlated primary cosmic rays are neutral, thus removing the motivation for restricting the analysis to events with energies above some arbitrary threshold. A search for correlations with the entire HiRes stereo data set of 4495 events at all energies is justified.

Applying the analysis to the entire data set and Sample B gives $\ln \mathcal{R} = 6.16$ for $n_s = 31$, with $\mathcal{F} = 2 \times 10^{-4}$. This, of course, includes the effect of the correlated events above 10^{19} eV; for the independent sample of 4224 events below 10^{19} eV, we find $\ln \mathcal{R} = 3.10$ for $n_s = 22$, with $\mathcal{F} = 6 \times 10^{-3}$.

4.2. *Source Sample*

Sample B of BL Lac objects discussed above consists of 157 confirmed BL Lac objects in the 10th Veron Catalog with optical magnitude $m < 18$ that are classified as "BL." The rest of the confirmed BL Lac objects are classified as "HP" (high polarization). It is natural to ask about these objects as well. Indeed, of the six blazars which have confirmed detections in γ-rays at TeV energies, half are classified as "HP" and half as "BL" in the Veron catalog.

We apply the same cut on optical magnitude $m < 18$ as in sample B to the "HP" objects, and arrive at a sample of 47 objects. The result of the maximum likelihood analysis applied to this independent sample of BL Lac objects and the HiRes events above 10^{19} eV is $\ln \mathcal{R} = 3.13$ for $n_s = 3.0$, with $\mathcal{F} = 6 \times 10^{-3}$. We also perform the same analysis on the events below 10^{19} eV. No excess is found. The results for HiRes events of energy above 10^{19} eV and all energies with BL Lac objects classified as "BL," "HP," or "BL + HP" combined are summarized in Table 2.

The equivalent analyses have been performed on the same classes of BL Lac objects with $m \geq 18$: no excess correlation is found in any of these cases. It is apparent from these results that the $m < 18$ cut that was identified in Tinyakov & Tkachev (2002) as optimal for AGASA also isolates the BL Lac objects that show excess correlations with HiRes events. Under the BL Lac source hypothesis, of course, it is not unreasonable to expect the closer and more luminous objects to contribute more strongly. However, since the Veron catalog is not a uniform sample of BL Lac objects, the interpretation of this cut may involve a more complicated interplay of selection effects from the underlying surveys that make up the catalog.[8]

TABLE 2

HiRes-BL Lac Correlation Results: Fraction $\mathcal{F}$ of Simulated HiRes Sets with Stronger Correlation Signal

Source Sample (No. Objects)	All Energies	$E > 10$ EeV
BL (157)	2×10^{-4}	2×10^{-4}
HP (47)	0.3	6×10^{-3}
BL + HP (204)	5×10^{-4}	10^{-5}

Note.—Correlations are with confirmed BL Lac objects in Table 2 of the Veron 10th Catalog (Veron-Cetty & Veron 2001), classified as either BL or HP, with $m < 18$.

TABLE 3

TeV Blazar Correlation Results with HiRes Events (All Energies)

TeV Blazars			Correlation Results		
Name	z	V mag	n_s	$\ln \mathcal{R}$	$\mathcal{F}$
Mrk 421	0.03	12.9	0.3	0.04	0.2
H1426+428	0.13	16.5	(0)[a]	(0)	0.4
Mrk 501	0.03	13.8	3.3	5.27	6×10^{-4}
1ES 1959+650	0.05	12.8	2.0	2.87	8×10^{-3}
1ES 2344+514	0.04	15.5	(0)[b]	(0)	0.7
Combined Set.......	. . .	. . .	5.6	4.78	10^{-3}

[a] No excess: $n_s < 3.5$ at 90% confidence level.

[b] No excess: $n_s < 2.4$ at 90% confidence level.

4.3. *TeV Blazars*

Among the closest and brightest of the "BL" and "HP" BL Lac objects are six that are confirmed sources of TeV γ-rays (Horan & Weekes 2004). Five of these, shown in Table 3, are high in the northern sky and well within the field of view of HiRes. We perform the maximum likelihood analysis on this set of objects using all of the HiRes data, and find $\ln \mathcal{R} = 4.78$ for $n_s = 5.6$ with $\mathcal{F} = 10^{-3}$. For just the HiRes events above 10^{19} eV, the result is $\ln \mathcal{R} = 6.15$ for $n_s = 2.0$ with $\mathcal{F} = 2 \times 10^{-4}$. In Table 3, we show the results for treating each blazar in turn as a single-source hypothesis.

5. RESULTS AND DISCUSSION

In this paper, we have used an unbinned maximum likelihood method to analyze correlations of ultrahigh-energy cosmic-ray arrival directions with BL Lac objects in the Veron 10th Catalog. We first tested previous claims of correlations between BL Lac objects and cosmic rays that were based on AGASA and Yakutsk data. Using the independent HiRes stereo data set, these correlation claims are excluded at the 99% (claims 1 and 3 in Table 1) or 90% confidence level (claim 2).

However, we have verified the observation by Gorbunov et al. (2004) that the set of HiRes stereo events with energies above 10^{19} eV shows an excess of events correlated with confirmed BL Lac objects marked as "BL" in the Veron 10th Catalog. We emphasize that the observed correlation does not confirm a previous claim, because it requires a lower energy threshold. It can only be confirmed with new data.

We have explored the extension of the analysis to (1) HiRes events of all energies, and (2) the rest of the confirmed BL Lac objects (labeled "HP") in the Veron 10th Catalog. In each case, correlations at the significance level of ~0.5% are found. While statistically independent from the above result, these are not strictly tests of that claim. However, the combination offers well-defined hypotheses which can be tested with new data.

The results of combining the analysis of low- and high -energy events and "BL" and "HP" BL Lac objects are summarized in

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[8] The Veron catalog strives to be "complete" only in the sense of a complete survey of the literature and catalog of all known BL Lac objects; it does not represent an unbiased statistical sample of BL Lac objects in any way (Veron-Cetty & Veron 2000, 2001). This does not exclude the possibility of using subsets of the catalog to identify correlations with cosmic rays, but it means that any inferences about the BL Lac objects based on such correlations may be highly biased and simply an artifact of the underlying combination of different surveys in the catalog.

TABLE 4

HiRes-BL Lac Correlation Summary: Fraction $\mathcal{F}$ of Simulated HiRes Sets with Stronger Correlation Signal

Source Sample (No. Objects)	All Energies	$E > 10$ EeV
BL Objects, $m < 18$ (157)	2×10^{-4}	2×10^{-4}
Confirmed BL Lac objects, $m < 18$ (204)	5×10^{-4}	10^{-5}
Confirmed TeV Blazars (6)	10^{-3}	2×10^{-4}

Notes.—All samples are contained within Table 2 of the Veron 10th Catalog. The samples overlap and are *not* independent: "Confirmed BL Lac objects" combines BL and HP classified BL Lac objects; TeV Blazars are a subset of the confirmed BL Lac objects.

Table 4. Also shown are the results for HiRes events and the subset of BL Lac objects that are confirmed sources of TeV γ-rays.

The analyses described here have only been performed on the data recorded through 2004 January. The HiRes detector will continue observations through the end of 2006 March. By that time, the independent sample of data since 2004 January is expected to reach approximately 70% of the size of the sample analyzed here. This will provide an opportunity to test the correlations in Table 4. We note that while the correlation signals appear stronger for the events above 10^{19} eV, a conservative approach that includes consideration of the entire data set will avoid the possibility that a real correlation has been "overtuned" by an arbitrary threshold and is missed in a future analysis.

As mentioned earlier, real correlations on the scale of the detector angular resolution would suggest neutral cosmic-ray primaries for these events, or at least that the primaries were neutral during significant portions of their journey through galactic and extragalactic magnetic fields. Primaries such as neutrons and photons are problematic, however, because of short mean free paths ($\sim$a few Mpc) at these energies.

Air fluorescence detectors measure the height of the maximum of the shower development, $X_{\rm max}$, a parameter that has some sensitivity to the primary particle type. Showers induced by photons, for example, tend to develop lower in the atmosphere than those induced by nucleons. HiRes stereo determines $X_{\rm max}$ with a typical accuracy of 30 g cm^{-2} (Abbasi et al. 2005a). As shown in Vankov et al. (2003), the difference in the mean $X_{\rm max}$ for proton- and photon-induced showers is about 200 g cm^{-2} at 10^{19} eV, but fluctuations are large, with standard deviations around 70 g cm^{-2}. At higher energies, the ability to distinguish photon from proton showers additionally depends on the direction through which the photon traverses Earth's magnetic field, because geomagnetic cascading will lower the mean $X_{\rm max}$ of photon showers substantially. The efficiency with which photon showers can be distinguished from proton showers is therefore different for each event. By accounting for these dependencies, we can estimate the number of BL Lac-correlated events consistent with photon primaries. This analysis is currently underway, and results will be published in a separate paper.

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