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Searching for the origin of ultrahigh energy cosmic rays with the High Resolution Fly's Eye Stereo Detector

Stefan Westerhoff[a] for the High Resolution Fly's Eye (HiRes) Collaboration *

[a]Columbia University, Department of Physics,
538 West 120 Street, New York, NY 10027, USA
westerhoff@nevis.columbia.edu

The High Resolution Fly's Eye (HiRes) experiment in Utah is an air fluorescence telescope mapping the sky in cosmic rays at energies above 10^{18} eV. Since November 1999, HiRes has been operated in stereo mode to provide cosmic ray data of unprecedented quality of the northern sky. This paper focuses on recent results from the stereoscopic data. We present a measurement of the primary chemical composition above 10^{18} eV, results on the search for small-scale anisotropies in the cosmic ray arrival distribution, and results on a search for point sources in the combined AGASA and HiRes stereo data set above 4.0×10^{19} eV.

1. Introduction

Among the most striking astrophysical phenomena today is the existence of cosmic ray particles with energies in excess of 10^{20} eV. While their presence has been confirmed by a number of experiments, it is not clear where and how these particles are accelerated to these energies and how they travel astronomical distances without substantial energy loss.

Several quantities that can help to solve these problems are accessible to experiment: mainly the *flux* of cosmic rays, their *chemical composition*, and, at the highest energies, where deflections in magnetic fields are expected to be small, their *arrival direction*. The High Resolution Fly's Eye (HiRes) Experiment [1] in Utah is an experiment to study ultrahigh energy cosmic rays above 10^{18} eV. Recent results include measurements on all main aspects of cosmic ray physics, including a new measurement of the proton-air cross section at $10^{18.5}$ eV [2].

This paper gives a summary of some recent results, with a strong emphasis on the data taken in stereoscopic mode. After a short discussion of measurements of the energy spectrum and the chemical composition of cosmic rays, the main part of the paper is dedicated to a study of the arrival direction distribution of cosmic rays above 10^{19} eV.

2. HiRes Stereo

HiRes is a stereo air fluorescence experiment with two sites (HiRes 1 and 2) at the US Army Dugway Proving Ground in the Utah desert (112° west longitude, 40° north latitude, with a vertical atmospheric depth of 860 g/cm^2). The two sites are separated by a distance of 12.6 km.

The ultrahigh energy cosmic ray flux is small and is a steeply falling power law in energy. Thus experiments at ultrahigh energies need a large detector volume. Consequently, the primary cosmic ray particles can not be observed directly, since they interact in the upper atmosphere and induce extensive air showers with of the order of 10^{10} particles for a 10^{19} eV primary. The properties of the original cosmic ray particle, such as arrival direction and energy, have to be inferred from the observed properties of the extensive air shower. In HiRes, this is achieved by observing the fluorescence light produced when particles of the extensive air shower interact with nitrogen molecules in the atmosphere. This method has the advantage that the shower development in the atmosphere is imaged and important quantities like the shower size and the height of the shower maximum can be determined directly. The main

*See http://hires.phys.columbia.edu for a complete list of authors

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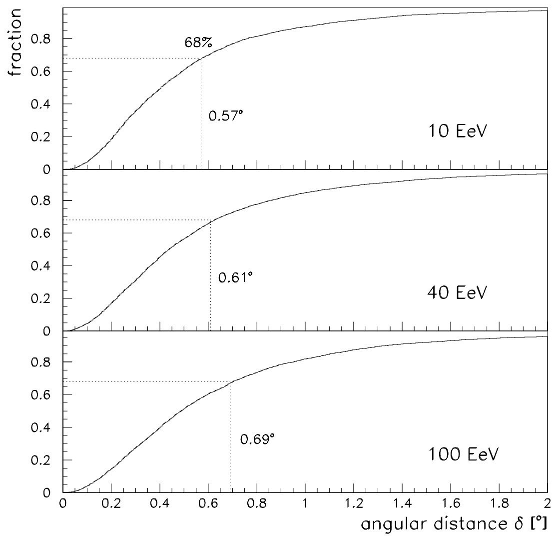

Figure 1. *Angular resolution of HiRes stereo for energies 10, 40, and 100 EeV. The plot shows the fraction of simulated events reconstructed within δ degrees of the true arrival direction, as a function of δ.*

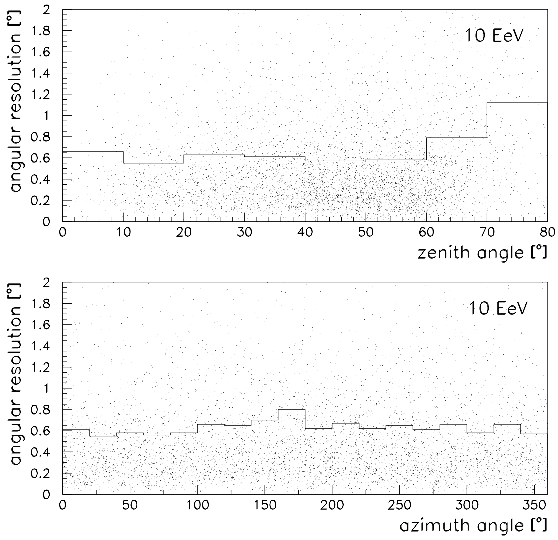

Figure 2. *Angular resolution as a function of zenith angle (top) and azimuthal angle (bottom) for simulated showers with energy $E = 10\,EeV$. The scatter plot shows individual events, the solid line represents the angular distance which includes 68 % of all events in the zenith or azimuthal angle bin.*

shortcoming of the technique is the low duty cycle of only about 10 %, since air fluorescence detectors can only be operated on dark, moonless nights with good atmospheric conditions.

To observe fluorescence light from air showers, the detector at each site comprises several telescope units monitoring different parts of the night sky. With 22 (42) telescopes at the first (second) site, the full detector covers about 360° (336°) in azimuth and $3^\circ - 16.5^\circ$ ($3^\circ - 30^\circ$) in elevation above horizon. Each telescope consists of a mirror with an area of about $5\,\mathrm{m}^2$ for light collection and a cluster of 256 photomultiplier tubes in the focal plane.

In monocular reconstruction, the so-called shower detector plane, which is the plane that contains the shower track and the detector, is very well-defined, whereas the location of the shower within that plane has to be reconstructed from the trigger times of individual phototubes along the shower track. This leads to fairly large errors, of order several degrees, on the angle describing the shower in the plane. The ambiguity is resolved if the shower is seen by two detectors. Stereo data has the distinct advantage that error bars on the arrival direction are fairly symmetric for most azimuthal angles. A global χ^2-minimization using all available information, including the tube trigger times, gives an angular resolution which is typically about half a degree. From measurements of laser tracks and stars in the field of view of the cameras we estimate that the systematic error in the arrival direction determination is not larger than 0.2°, mainly caused by uncertainties in the survey of mirror pointing directions. Various aspects of the HiRes detector and the reconstruction procedures are described in [1,3,4].

The angular resolution of HiRes is determined using simulated showers. We use a full detector simulation of proton showers generated with CORSIKA 6 [5] using QGSJET for the first interaction. The showers are thrown isotropically and undergo a full detector simulation and event reconstruction including all cuts that are applied to the real data [6]. As shown in Fig. 1, 68 % of all showers generated at 10^{19} eV are reconstructed within less than 0.57° of the true shower direction. The angular resolution depends weakly on energy; the 68 % error radius grows to 0.61° and 0.69° for showers generated at $4.0 \cdot 10^{19}$ eV and 10^{20} eV, respectively, because at higher energies, showers are on average farther away.

Fig. 2 shows the angular distance between true and reconstructed shower direction for a large number of showers with energy $E = 10^{19}$ eV as a function of zenith and azimuthal angles of the arrival direction. The angular resolution is essentially constant in zenith and azimuthal angles, varying by less than 0.1° for zenith angles less than 70°. There is a small range of azimuthal angles where the angular reconstruction is worse: for azimuthal angles where the shower and the two sites are in the *same* plane, the stereo reconstruction looses its advantage and is essentially reduced to a monocular reconstruction. Showers having poor angular resolution as a result of this ambiguity fail the quality cuts.

The reconstruction uses an hourly atmospheric data base built from reconstructed laser shots. Note that stereo data provides us with a consistency check regarding the weather corrections applied to the data. If the distance of the shower to the two detectors is notably different, any inaccurate correction for light scattering and absorption will result in a mismatch of energy estimates for the two sites.

3. Composition and spectrum

The study of the chemical composition and the flux of cosmic rays is an important tool to reveal their origin. In our current understanding, there is a change in the origin of cosmic rays between $10^{17.5}$ and $10^{18.5}$ eV. While the cosmic ray flux below 10^{18} eV is Galactic in origin, extragalactic sources take over at the highest energies. This picture is supported by the change in the spectral index of the cosmic ray energy spectrum near $10^{18.5}$ eV, often referred to as the "ankle."

The ankle feature of the spectrum has recently been confirmed by measurements with the HiRes detector operating in monocular mode [7]. At this point, it is too early for a reliable and statistically convincing result on the spectrum based on stereo data. However, the ankle shows up clearly in the monocular HiRes 2 spectrum at $10^{18.5}$ eV. Fitting the spectrum to a broken power law gives a break point at $\log(E/\mathrm{eV}) = (18.47 \pm 0.06)$ with a spectral slope of $\gamma = 3.32 \pm 0.04$ below and $\gamma = 2.86 \pm 0.04$ above the ankle.

Another indication for a change in cosmic ray origin at around 10^{18} eV comes from measurements of the chemical composition. Since the Galactic flux is expected to be dominated by heavier nuclei like iron and the extragalactic flux should be mainly protons, we expect the chemical composition to change at energies around the ankle. This has been observed with an earlier prototype of the HiRes detector [8], HiRes-MIA (although the interpretation of these measurements has recently been criticized [9]).

Measuring the chemical composition of the cosmic ray flux is one of the strengths of air fluorescence detectors. With this detector type, we directly measure the atmospheric depth of the shower maximum, X_{max}, which is an indicator of the nature of the primary particle. Heavier nuclei induce an earlier shower development, so their shower maximum is higher up in the atmosphere than it is for protons. However, due to the large intrinsic fluctuations in the depth of the shower maximum, it is not possible to identify the chemical nature of the incoming cosmic ray on a shower-by-shower basis with any reasonable certainty. Only quantities averaged over a large number of showers can be used as indicators for the cosmic ray composition at a given energy. Simulations predict that the mean atmospheric depth of the shower maximum, $< X_{max} >$, increases logarithmically with primary energy E and differs by about $100\,\mathrm{g\,cm^{-2}}$ for proton- and iron-induced showers at all energies. The slope, $d(< X_{max} >)/d(\log E)$, is known as the elongation rate.

The elongation rate between 10^{18} eV and $10^{19.4}$ eV has recently been measured with the HiRes stereo detector [10]. The analysis is based on data taken between November 1999 and September 2001. The elongation rate is measured to be $(54.5 \pm 6.5(\mathrm{stat}) \pm 4.5(\mathrm{sys}))$ g cm^{-2} per decade. This elongation rate and the width of the X_{max} distribution is consistent with a constant and predominantly light composition. For a simulated data set of only proton and iron nuclei, the best agreement with predictions based on the QGSJet01 and SYBILL 2.1 hadronic interaction codes is observed for a composition of 80 % protons and 20 % iron.

4. Study of arrival directions

At energies above several 10^{18} eV, cosmic ray particles are believed to be of extragalactic origin. If charged cosmic ray particles do not suffer considerable deflections in Galactic and extragalactic magnetic fields, one can hope to identify the sources and understand the underlying acceleration mechanism by a detailed study of their arrival directions. The strength and orientation of these fields is poorly known and estimates vary [11,12], but their impact should decrease at the largest energies; here, cosmic ray astronomy might be possible.

The small cosmic ray data set has been subjected to extensive searches for clustering of arrival directions on small angular scales, and there have been a variety of attempts to correlate catalogs of known astrophysical sources with cosmic ray arrival directions.

So far, all efforts to identify the sources from the sparsely populated sky map have not produced statistically convincing evidence for small-scale clustering or correlations with any class of objects. "Statistically convincing" should be emphasized here, as there is actually no shortage of claims for both clustering and correlation with catalogs. Small-scale clustering of ultrahigh energy cosmic rays above 4.0×10^{19} eV has, for example, been repeatedly reported [14–19], with analyses mainly based on arrival directions recorded with the Akeno Giant Air Shower Array (AGASA) in Japan. If correct, these results could indicate that cosmic rays originate in nearby, compact sources.

However, there is considerable disagreement over the statistical significance of this clustering signal. The problem arises from the way the chance probability of the signal is evaluated. Quite often, the data set used to formulate the correlation hypothesis is also used for evaluating its significance. Problems with published claims of significant small-scale clustering have been pointed out by various authors [20–22], and it has become clear that ultimately, only statistically independent data sets will allow a rigorous test of these claims.

The stereo HiRes detector currently provides us with the *sharpest image* of the northern sky in ultrahigh energy cosmic rays. The stereo data set allows for independent tests of previous claims that the arrival direction of ultrahigh energy cosmic rays shows statistically significant small-scale clustering. We can also study whether there is evidence for a point source in the *combined* AGASA and HiRes stereo data set above 4.0×10^{19} eV.

4.1. Small-scale clustering

As described in [6], we search for small-scale clustering by performing a two-point correlation scan in energy and angular separation. For a given energy E, we count the number of pairs n_p separated by less than θ. We then use sets of simulated showers with the same number of events as the HiRes stereo data set, but with an isotropic distribution of arrival directions, to estimate the chance probability $P(E, \theta)$ of finding n_p or more pairs in a random data set just by chance. We identify the energy threshold E_{min} and the angular distance θ_{min} which give the smallest chance probability, P_{min}. This is the most promising potential clustering signal, and its statistical significance can be determined by performing the same scan over n_{MC} data sets with isotropic arrival directions, finding the minimum probability for each of these sets, and counting the number of data sets for which $P < P_{min}$. Simulations show [6] that despite the statistical penalty incurred by scanning, this procedure results in a final chance probability of about 1 % (2×10^{-3} %)

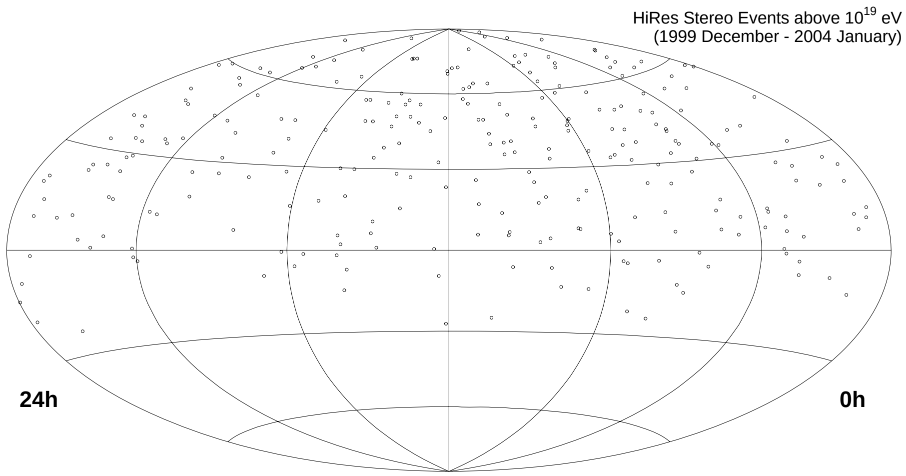

Figure 3. *Arrival directions in equatorial coordinates for 271 HiRes stereo events above 10 EeV recorded between December 1999 and January 2004.*

for as few as 3 (4) clusters in 47 events, assuming that cosmic rays are not subject to strong deflections in magnetic fields.

For the HiRes stereo data set, we perform this scan over the events with energies above 10^{19} eV. 271 events above 10^{19} eV recorded between December 1999 and January 2004 survive the quality cuts described in [6]. Fig. 3 shows a sky map of their arrival directions in equatorial coordinates.

We scan from 0° to 5° in steps of 0.1° in angular separation. The energy threshold E_{min} is lowered one event at a time, starting at the highest energy event and decrementing to 10^{19} eV.

For the HiRes stereo data set, the strongest potential signal is found at $E_{min} = 1.69 \times 10^{19}$ eV and $\theta_{min} = 2.2°$. The chance probability for this potential signal is $P_{min} = 1.9\,\%$, but the final chance probability after accounting for the scan is $P_{ch} = 52\,\%$. The signal is therefore not significant, and we conclude that the HiRes stereo data above 10^{19} eV is consistent with the null hypothesis of isotropic arrival directions. As a consequence of our approach, we find that this conclusion is indeed very general. There is no evidence for significant clustering for any energy threshold above 10^{19} eV on all angular scales of 5° or less. This indicates that clustering of arrival directions is weaker than previously suggested and might not be a general feature of ultrahigh energy cosmic rays after all.

4.2. Search for point sources

The published AGASA data set and the HiRes stereo data set overlap only a few months in time, but both detectors observe approximately the same part of the northern sky. With 27 events above 4.0×10^{19} eV recorded through January 2004, the HiRes data set now contributes significantly to the world ultrahigh energy data set: thus it becomes increasingly interesting to search for possible point sources in this *combined* data set.

In combining the two data sets, we need to account for the different errors on the individual cosmic-ray arrival directions as well as for the different background expectations in the two experiments. In addition, the analysis method should be “unbinned”, at least in the sense that any error from binning is much smaller than other errors in the data. This means that we do not define a fixed

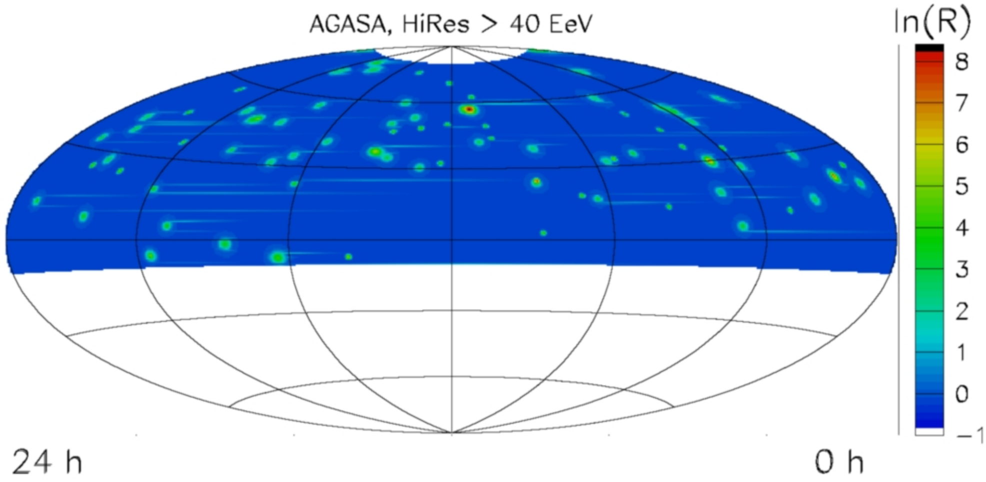

Figure 4. *Likelihood ratio* $\ln \mathcal{R}$*, maximized with respect to* n_s*, as a function of right ascension and declination for the combined set of AGASA and HiRes events above* $4.0 \times 10^{19}\,eV$*. Local maxima occur wherever events or clusters of events are located on the sky.*

maximum angular separation for events to form a multiplet. Rather, we search over the whole HiRes/AGASA sky for possible point source positions.

For analyzing a data set comprising events with very different errors, the maximum likelihood method is particularly well suited. We perform a likelihood ratio test of the hypothesis that several events in the sky map come from a common source. In other words, we test whether any given position on the sky harbors a source which contributes $n_s \geq 1$ source events to the data set. The likelihood of this hypothesis is compared to the null hypothesis $n_s = 0$ and this likelihood ratio is maximized using n_s as a free parameter. By calculating the likelihood ratio for a dense grid of points on the sky, we essentially search the entire sky for the most likely position of a source of n_s events. The statistical significance can be estimated by applying the same method to a large set of random isotropic data sets and evaluating what fraction of them have a maximum likelihood ratio which is equal to or larger than the ratio observed in the real data described above. Details on the maximum likelihood method used here are given in [13].

The likelihood technique applied here makes use of the probability density functions for signal and background. For signal, the probability density function is the normalized probability for finding an event with a true arrival direction $\vec{x}_s$ at some location $\vec{x}$, so it is basically the point-spread function of the detector. For HiRes events, we use a two-dimensional Gaussian function whose width is chosen such that 68 % of the probability density function falls within an opening angle $0.6°$. Since the dependence on energy is weak, we use the same value for every HiRes stereo event. For AGASA, we approximate the probability density by the sum of two two-dimensional Gaussian functions chosen such that the 68 % and 90 % opening angles given in [15] are correctly re-

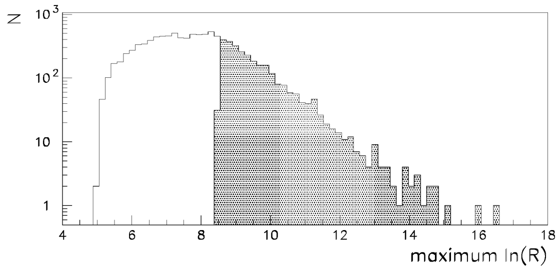

Figure 5. *Maximum* $\ln\mathcal{R}$ *for* 10^4 *simulated random data sets with the same number of AGASA/HiRes events as the actual data set. The hatched area marks random sets whose maximum* $\ln\mathcal{R}$ *exceeds the value for the real data set.*

produced.

The probability density function for background is the normalized relative exposure of the detector to an isotropic background of cosmic rays. It depends on the detector exposure to different parts of the sky and is the same function for all events observed by a given detector.

Fig. 4 shows the result of the analysis. At each right ascension α and declination δ, the likelihood ratio $\ln\mathcal{R}$ is shown for the number of source events n_s which maximizes $\ln\mathcal{R}$. One can clearly recognize where events are located, and one can also recognize locations with several nearby events. AGASA and HiRes events can easily be distinguished, because the latter have better resolution and therefore smaller regions with large likelihood. The point with the largest $\ln\mathcal{R}$ is at $\alpha = 169.3° \pm 1.0°$ and $\delta = 57.0° \pm 0.5°$. The best estimate of the number of source events is $n_s = 2.9^{+2.0}_{-1.4}$. The corresponding event cluster comprises 3 nearby AGASA events with coordinates (α, δ) and energies E of (1) $(168.5°, 57.6°)$, $E = 77.6\,\mathrm{EeV}$, (2) $(172.3°, 57.1°)$, $E = 55.0\,\mathrm{EeV}$, and (3) $(168.3°, 56.0°)$, $E = 53.5\,\mathrm{EeV}$. This cluster has been described in [15] and is listed as cluster C2 in [16]. The maximum likelihood ratio at this position is $\ln\mathcal{R} = 8.54$.

The statistical significance of the appearance of a "source" with a maximum likelihood ratio $\ln\mathcal{R}$ in the combined AGASA/HiRes data set can be evaluated using simulated random data sets. The full likelihood analysis is performed for 10^4 random data sets with the same number of AGASA/HiRes events and the same underlying exposure as the original data set, but isotropic arrival directions. The chance probability for the "source" to appear is then given by the fraction of random data sets which have at least one location causing the maximum $\ln\mathcal{R}$ to be equal or larger than 8.54, the value of the maximum in the real data.

Fig. 5 shows the distribution of the maximum $\ln\mathcal{R}$ for each of these random data sets. Out of 10^4 simulated data sets, 2793 have a maximum $\ln\mathcal{R}$ exceeding that of the real data set. The chance probability of the source hypothesis is therefore of the order of 28 %. Consequently, there is no statistically significant evidence for clustering consistent with a point source in the combined data set.

Note that this is *not* simply the chance probability for a triplet, but rather the chance probability for a set of 27 HiRes events and 57 AGASA events to contain a "hot spot" with as high a probability to be a "source" as the triplet. Many of the simulated likelihood ratios larger than 8.54 in Fig. 5 are indeed caused by doublets.

The chance probability of the triplet using AGASA data alone has been estimated in [19] as being of order 1 %. This estimate is based on a fixed bin size of 2.5°. To test what chance probability an unbinned analysis gives, we repeat the likelihood analysis for the data set comprising only the 57 AGASA events above $4.0 \times 10^{19}\,\mathrm{eV}$. The largest likelihood ratio ($\ln\mathcal{R} = 9.66$) appears again near the events forming the triplet, with $\alpha = 169.3° \pm 1.0°$ and $\delta = 57.0° \pm 0.5°$ for $n_s = 2.9^{+2.0}_{-1.4}$.

As before, we evaluate the chance probability for the appearance of a source with maximum $\ln\mathcal{R} = 9.66$ or higher in this data set by analyzing a large number of simulated isotropic data sets, now containing 57 AGASA events. 452 out of 10^4 random data sets have a maximum $\ln\mathcal{R}$ in excess of 9.66, so the chance probability is 4.5 %.

The increase over the chance probability given in [19] reflects the fact that the AGASA bin size of 2.5° was chosen *a posteriori* in [14] as the bin size that maximizes the clustering signal in the AGASA data set. The unbinned maximum likelihood analysis removes this bias.

HiRes is currently the only detector observing the cosmic ray sky from the northern hemisphere. We anticipate several more years of data taking, and the search for cosmic ray point sources at the highest energies will continue when more data becomes available.

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