Search for intrinsic anisotropy in the UHECRs data from the Pierre Auger Observatory

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***Abstract*. We discuss techniques which have been developed for determining the intrinsic anisotropy of sparse ultra-high-energy cosmic ray datasets, including a two point, an improved two point and a three point method. Monte-Carlo studies of the sensitivities of these tests are presented. We perform a scan in energy above the 100 highest energy events (corresponding to ≃43 EeV) detected at the Pierre Auger Observatory and find that the largest deviation from isotropic expectations occurs for events above 52 EeV.**

***Keywords*: UHECRs, anisotropy, autocorrelation**

I. Introduction

The origin of ultra-high energy cosmic rays (UHECRs) with energies greater then 10^{18} eV has been a longstanding mystery since their discovery about 50 years ago [1]. The Pierre Auger Collaboration has recently shown that the flux of cosmic rays is strongly suppressed above 4×10^{19} eV [2], providing evidence for the 1966 prediction of Greisen [3] and of Zatsepin and Kuz'min [4] (GZK). The effect of energy losses combined with the anisotropic distribution of matter in the 100 Mpc volume around us suggests that cosmic rays at the highest energies are likely to be distributed anisotropically. This expectation of anisotropy above the GZK threshold was verified in 2007 [5], [6], when the Auger Collaboration reported an evidence for anisotropy at a C.L. of at least 99% using the correlation of the cosmic rays detected at the Pierre Auger Observatory with energies above $\sim 6 \times 10^{19}$ eV and the positions of the galaxies in the Veron-Cetty & Veron [7] (VCV) catalogue of active galactic nuclei (AGNs).

Here we report on tests designed to answer the question of whether the arrival directions of the highest-energy events observed by Auger are consistent with being drawn from an isotropic distribution, with no reference to an association with AGN or other extragalactic objects. The goal is to test for anisotropy using only the cosmic-ray data.

II. Statistical methods

At the highest energies, the steepening of the energy spectrum makes the current statistics so small that a measure of a statistically significant departure from isotropy is hard to establish, especially when using blind generic tests. This motivated us to test several methods by challenging their power for detecting anisotropy using simulated samples with few data points (typically less than 100) drawn from different kinds of anisotropies both in large and small scales. We report in this paper on auto-correlation analyses, using differential approaches based on a 2pt function, an extended 2pt function (refered to as 2pt+ in the following), and a 3pt function.

The standard 2pt function [8] was used as a reference. We histogrammed the number of event pairs within a given angular distance in bins of 5° and compared it to the isotropic expectation obtained from a large number (typically 10^6) of Monte-Carlo samples. The departure from isotropy is then measured through a pseudo-log-likelihood Σ_P:

$$\Sigma_P^{data} = \sum_{i=1}^{N} \ln \mathcal{P}(n^i_{obs} | n^i_{exp}),$$

where n^i_{obs} and n^i_{exp} are the observed and expected number of event pairs in bin i and $\mathcal{P}$ the Poisson distribution. The resulting Σ_P^{data} is then compared to the distribution of Σ_P obtained from isotropic Monte-Carlo samples. The probability P for the data to come from the realisation of an isotropic distribution is calculated as the fraction of samples having Σ_P lower than Σ_P^{data}.

A statistics was constructed to add the orientation information of the event pairs to the 2pt information[9]. The new estimator, 2pt+, is calculated on the data and on a large set of Monte-Carlo samples in the same way than in the 2pt case. Again, the departure from isotropy is measured by the fraction of samples giving a 2pt+ estimate smaller than the data.

Finally, we also constructed a 3pt method based on [10] where, for each triangle defined by a triplet of data points, a shape (round or elongated) and a strength (small or big) parameter can be calculated. The 2 dimensional distribution of these parameters from the data is then compared to the average expectation from a large set of Monte-Carlo samples of the same size by means of the same log-likelihood method with Poisson statistics than in the previous cases. More details can be found in [11].

III. Monte-Carlo studies

A test is usually defined in terms of a *threshold* α, which is the probability against the wrong rejection of the null hypothesis (in our case wrongly rejecting isotropy or claiming an anisotropy while there is not), and of a *power* $1 - \beta$, which is the probability to

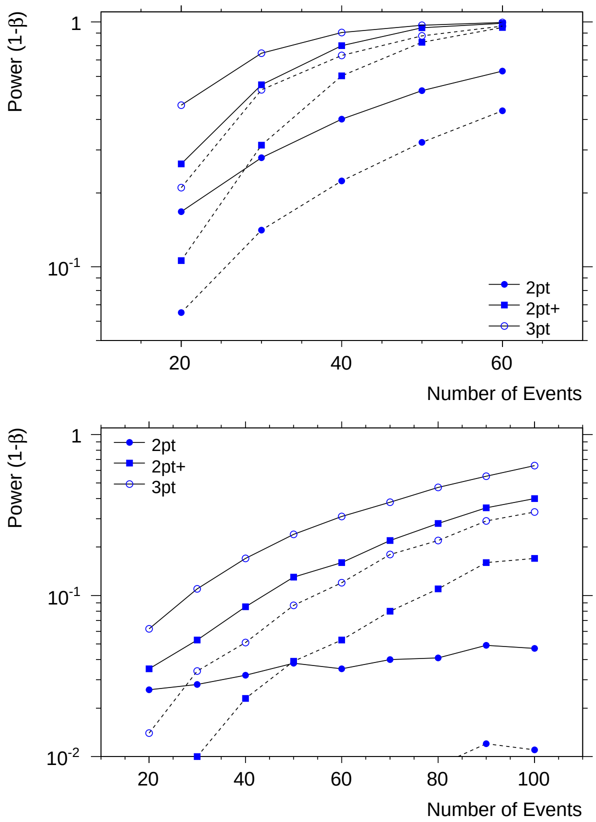

Fig. 1. Power of the 2pt (filled circles), 2pt+ (filled squares) and 3pt (empty circles) tests as a function of the number of events, for 2 threshold values: 1% (lines) and 0.1% (dotted lines). Events are drawn from nearby ($z \leq 0.018$) AGN from [7] with no isotropic background (upper panel) and 50% isotropic background (lower panel).

successfully claim anisotropy when it exits. A good test is a test that for a given number of events and a given threshold α has a high power $1 - \beta$. When the power of a test is less than 90%, the test may often miss a true signal. In this section, we present the power of the three tests at different thresholds α as a function of the number of events, based on mock samples inspired from the correlation of UHECRs with nearby extragalactic objects we reported in [5], [6].

We first built fair samples of the VCV catalogue of AGNs with redshift $z \leq 0.018$, accounting for the exposure function of the experiment. On the upper panel of Fig.1, we show the power of the 2pt test (filled circles), of the 2pt+ test (filled squares) and of the 3pt test (empty circles) as a function of the number of events. Two thresholds are illustrated: $\alpha = 1\%$ (lines) and $\alpha = 0.1\%$ (dotted lines). Whatever the number of events, the 2pt+ and 3pt tests are always more powerful than the standard 2pt one, and this is even more the case when the number of events decreases. Meanwhile, below 50 events, the power of each test is rapidly getting lower even in the case of a 1% threshold, reaching only less than 50% at best with 20 events.

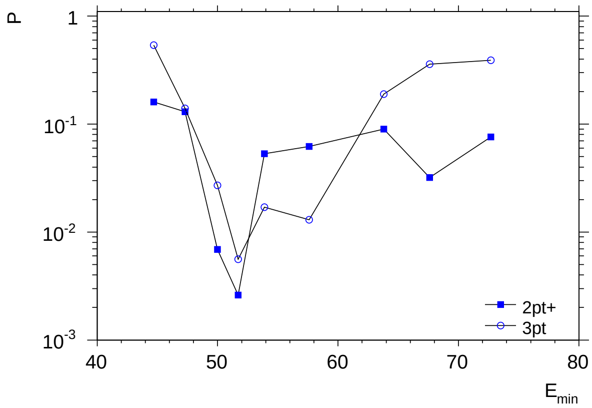

Fig. 2. Significance of the anisotropy in the highest energy events as a function of E_{min}. Filled squares (empty circles) are the probability values calculated using the 2pt+ method (3pt method). The largest departure from isotropy is found at energy of about 52 EeV.

We show the same analysis on the lower panel of Fig.1 but by adding a 50% mixture of isotropic events to the anisotropic signal. All tests are then less sensitive than in the previous case, the power of the best of them (3pt) being always below 90% even with a threshold of 1%, and reaching only few % when dealing with 20 events.

It thus turns out that at low statistics, the sensitivity of the tests gets rapidly diluted, their power never reaching 90% unless a strong signal of anisotropy is present in the data set.

IV. Application to the Data

The data set we use in this analysis consists of the 100 highest energy events (corresponding to energies greater than $\simeq$43 EeV) with zenith angles smaller than 60° recorded by the surface detector of the Pierre Auger Observatory from January, 1^{st} 2004 to March, 31^{st} 2009. The energy resolution is 17%, with a systematic uncertainty fo 22% [2]. The angular resolution, defined as the angular radius around the true cosmic ray direction that would contain 68% of the reconstructed shower directions, is at these energies better than 0.9°[13]. The fiducial cut implemented in the present analysis requires that at least 5 active nearest detectors surround the one with the highest signal when the event was recorded, and that the reconstructed shower core is inside an active equilateral triangle of detectors.

Applying both 2pt+ and 3pt estimators, we performed a scan in energy to search for intrinsic anisotropy. We show in Fig.2 the results of this scan, starting from the 20 highest energy events ($E_{min} \simeq 73$ EeV), and lowering the energy threshold by adding each time the 10 next events up to the 100 highest energy events ($E_{min} \simeq 43$ EeV). The filled squares are the results obtained using the 2pt+ method, while the empty circles are the results obtained using the 3pt method. The maximal departure from isotropy is observed to occur at $\simeq 52$ EeV (for the 70 highest energy events) using both methods: at this energy threshold, the probability P for the data to be a realisation of an isotropic background is $P = 0.26\%$ using the 2pt+ estimator and $P = 0.56\%$ using the 3pt estimator. For higher energy thresholds, both methods give results above the % level. As expected from the second toy model described in the previous section, the relatively low power of the tests when lowering the number of events prevents us to conclude on the isotropic or anisotropic nature of the sky from these observations.

The numbers reported here do not take into account the penalties associated to the scan in energy. In any case, as all those analyses were performed *a posteriori*, this prevents us to rigorously report on probabilities that could be taken at face value.

In Fig.3, we illustrate the largest departure from isotropy we found in the data using the 3pt method, by showing the log-likelihood of individual bins in shape-strength parameter space of data above 52 EeV compared against isotropic expectations (upper panel). Because of bin-bin correlations, the method sums the log-likelihoods to obtain Σ_P^{data} and compares them against isotropic skies to determine the probability that an isotropic distribution may produce this pattern at random. The distribution of Σ_P for 2×10^4 isotropic skies is plotted with black hatching in the lower panel. As in the 2pt and the 2pt+ cases, the departure from isotropy is then obtained by counting the number of isotropic Monte-Carlo skies with a lower Σ_P than the one observed in the data.

V. Conclusion

We have reported three statistical methods to search for intrinsic anisotropy of the UHECRs data measured at the Pierre Auger Observatory. Despite of the sensitivity improvement that the 2pt+ and 3pt tests bring with respect to the standard 2pt test, they still show relatively low power at low statistics, as estimated on toy Monte-Carlo samples drawn with the help of catalogues of nearby astronomical objects. This makes difficult the detection of anisotropy independently of any catalogue of astronomical objects even at 99% confidence level with the current statistics we are dealing with at the highest energies. On the contrary, tests designed on correlation of UHECRs with the positions of nearby astronomical objects are more powerful to provide evidence for anisotropy [14], [15]. More statistics is clearly necessary to establish any anisotropy claim using the kind of blind generic tests we presented in this paper.

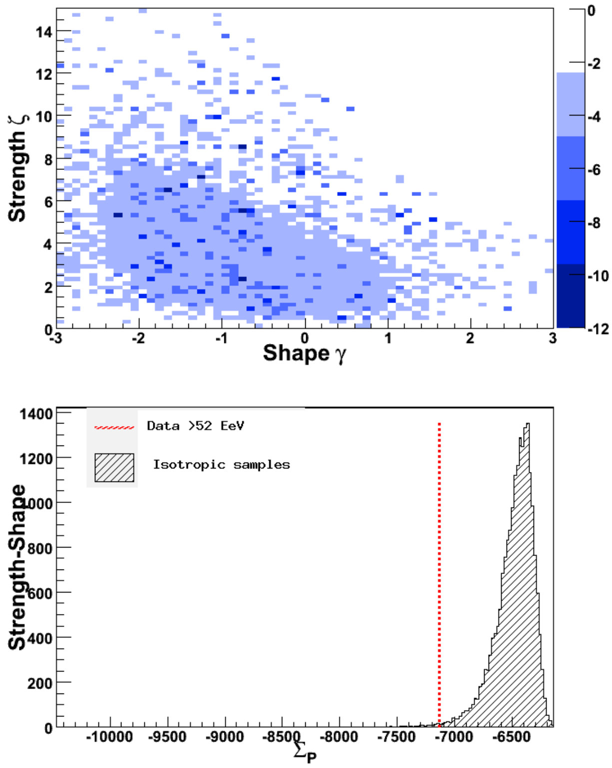

Fig. 3. Top: for each bin in shape and strength, we plot the natural-log of the Poisson probability to observe n_{obs} triplets given n_{exp} expected from an isotropic sky, in shades of blue. Bottom : The distribution of Σ_P for 2×10^4 isotropic skies is plotted with black hatching. The significance is calculated by counting the number of isotropic Monte-Carlo skies to the left of the data (dashed red line).

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