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Arrival directions of the highest-energy cosmic rays detected with the Pierre Auger Observatory

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We present the results of a search for small to intermediate scale anisotropies in the distribution of arrival directions of ultra-high energy cosmic rays recorded at the Pierre Auger Observatory. The data set, gathered in ten years of operation, includes arrival directions with zenith angles up to 80°, and is about three times larger than that used in earlier studies. We update the test based on correlations with active galactic nuclei (AGNs) from the Véron-Cetty and Véron catalog, which does not yield a significant indication of anisotropy with the present data set. We perform a blind search for localized excess fluxes and for self-clustering of arrival directions at angular scales up to 30° and for different energy thresholds between 40 EeV and 80 EeV. We also examine the correlation of arrival directions with relatively nearby galaxies in the 2MRS catalog, AGNs detected by Swift-BAT,and a sample of radio galaxies with jets and with the Centaurus A galaxy. None of the searches shows a statistically significant evidence of anisotropy. The two largest departures from isotropy that were found have a post-trial probability $\approx 1.4\%$. One is for cosmic rays with energy above 58 EeV that arrive within 15° of the direction toward Centaurus A. The other is for arrival directions within 18° of Swift-BAT AGNs closer than 130 Mpc and brighter than 10^{44} erg/s, with the same energy threshold.

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1. Introduction

The determination of the origin of the very high energy cosmic rays is a difficult task, mostly because of the very small value of their flux at Earth, together with the fact that they experience magnetic deflections during propagation. Nevertheless, the distribution of arrival directions might contain crucial information about the cosmic ray sources, provided that their distribution is not uniform and that the deflections are small enough. Such conditions could be fulfilled by low-Z cosmic rays with energies above ~ 40 EeV: the suppression of the flux that is observed [1] in the energy spectrum is compatible with a GZK [2] mechanism, thus potentially limiting the distance from which a source can contribute. Independently of the origin of this flux suppression, the recent upper-limits on the primary cosmic ray photon flux [3] severely constrain top-down models, thus favoring an astrophysical origin for the sources of cosmic rays.

The present paper describes the latest analysis of the distribution of arrival directions of cosmic rays with energies above 40 EeV detected at the Pierre Auger Observatory in 10 years of operation, with a total exposure of about 66,000 km^2 sr yr. After a brief description of the data set, we first present an update of the correlation analysis performed with the AGNs from the Véron-Cetty and Véron catalog [4]. The result of this test does not confirm the initial evidence of anisotropy that was observed [5] for cosmic rays with energies above 57 EeV. Consequently, we searched for the presence of a possible anisotropy in the distribution of arrival directions for events with energies above 40 EeV, applying different types of tests.

In section 2 we first analyze the distribution of arrival directions in the data set without using any external information such as a catalog of candidate sources. This search of intrinsic anisotropy is performed with the auto-correlation method, together with a search for excess of events in circular windows over the whole exposed sky.

In section 3, we study the cross-correlation between the cosmic ray arrival directions and the position of candidate sources extracted from catalogs. We describe the cross-correlation analysis performed with the 2MRS catalog of galaxies detected in IR, the 70 months Swift-BAT catalog of AGNs detected in X-rays, and with a catalog of radio galaxies. We describe in addition the analysis of the distribution of events around the direction of the Cen A galaxy. The details of all these analyses together with the list of arrival directions and energies of the events can be consulted in [6].

Data set The data set used in the present analysis consists of 602 events with energy above 40 EeV measured by the Surface Detector (SD) of the Pierre Auger Observatory between the 1st January 2004 and the 31st March 2014. The Pierre Auger Observatory is a 3000 km^2 array of water-Cherenkov detectors with 1.5 km spacing, overlooked by 24 fluorescence telescopes located on its periphery. A recent and detailed description of the detector can be found in [7].

The total data set is the combination of 454 events with zenith angle $\theta < 60^\circ$ (vertical events) and 148 events with $60^\circ < \theta^\circ < 80^\circ$ (inclined events). The extension of the zenith angle range, compared to previous anisotropy searches that were limited to vertical events, has two important advantages: a 30% increase of statistics and a higher fraction of the sky covered, ranging from -90° to $+45^\circ$ in declination.

The properties of the signal measured at ground being zenith angle dependent, the selection and reconstruction procedures are different for vertical and inclined events. The vertical events are selected if the water-Cherenkov detector that measured the highest signal is surrounded by at least four other operational detectors in the closest range. In addition, the reconstructed shower core position at ground must lie within a triangle of contiguous operational detectors. This event selection ensures an accurate event reconstruction and increases the number of vertical events by 14% with respect to the previous selection used in our analyses. The selection of inclined events requires the presence of 5 operational detectors around the one with the highest signal.

For both data sets, the detection and selection efficiency is 100% for the energies considered here, the exposure is therefore determined only by the geometry of the array and amounts to 51,753 and 14,699 km^2 sr yr for the vertical and inclined samples respectively.

The angular resolution, defined as the 68% containment radius around the true arrival direction, is better than 0.9° above 10 EeV [8], where a high number of detectors participate in an event. The ground estimator for the energy determination is different for vertical and inclined events: the vertical reconstruction uses the fitted signal at 1000 m from the shower axis whereas the inclined reconstruction estimates the muon content relative to a simulated proton shower with energy 10^{19} eV. In both cases, the final energy estimation uses the cross-calibration with the Fluorescence Detector (FD) that provide a quasi-calorimetric measurement. The statistical uncertainty in the energy determination is better than 12% above 10 EeV [9] and the systematic uncertainty in the absolute energy scale is 14%. As a consequence of the recent update of the absolute energy scale [10], the energy threshold of 55 EeV used in our previous publication [11] now corresponds to approximately 53 EeV.

Note on the anisotropy test with the VCV catalog The Véron-Cetty and Véron catalog of active galactic nuclei [4] has been previously used to search for correlation with potential cosmic ray extragalactic sources. The number of CR events with $E > E_{\rm th}$ that arrive within an angular distance Ψ of an AGN with redshift $z < z_{\rm max}$ is measured and compared to isotropic expectations. After an initial scan over the parameters with vertical events collected between the 1^{st} January 2004 and the 26^{th} May 2006, the most significant excess was found for $E_{\rm th} = 57$ EeV, $\Psi = 3.1°$ and a maximum redshift corresponding to a distance of 75 Mpc. This set of parameters has been used on subsequent independent data, leading to a correlation fraction of 61% with a 1.7×10^{-3} probability of happening by chance [5]. The analysis has been performed with increased statistics, leading to a much lower (38^{+7}_{-6})% correlation fraction [11]. An update of this analysis with the present vertical data set described previously yields a correlation fraction of $(28.1^{+3.8}_{-3.6})$ %, which is only 2 standard deviations above the isotropic expectation of 21%. We conclude that the present level of the correlation fraction does not provide a significant indication of anisotropy.

2. Intrinsic anisotropy tests

Search for a localized excess flux over the exposed sky We searched for an excess in the arrival directions of cosmic rays by counting the number of events that fall inside circular windows of varying radius Ψ from 1° to 30° in 1° steps. The centers of those windows cover the whole exposed sky and are located on a regular $1° \times 1°$ grid. An energy threshold $E_{\rm th}$ is applied to the events, and

is varied between 40 EeV and 80 EeV with 1 EeV steps. The number $n_{\rm obs}$ of observed events is compared to that expected from an isotropic flux $n_{\rm exp}$: the isotropic value $n_{\rm exp}$ is estimated by numerically integrating the geometric exposure function in the corresponding angular window. For each window we compute the binomial probability p of observing by chance in an isotropic flux a greater or equal number of events than that found in the data. A scan using the combined vertical and inclined data set was performed on the parameters Ψ and $E_{\rm th}$, leading to a minimum probability of $p = 5.9 \times 10^{-6}$ for an excess of $n_{\rm obs}/n_{\rm exp} = 14/3.23$ with $E_{\rm th} = 54$ EeV and $\Psi = 12^{\circ}$.

The Li-Ma significance [12] of event excesses with $E \geq 54$ EeV in windows of 12° radius is shown in Figure 1 (left). The highest significance region (4.3σ) is found to be close to the Super-Galactic Plane and to the CenA radiogalaxy. To quantify the significance of this excess, we simulated 10,000 isotropic data sets with the same number of events and applied the full parameter scan described above. In 69% of isotropic simulations an excess with p smaller than 5.9×10^{-6} can be found, hence indicating that the data are compatible with isotropic expectations.

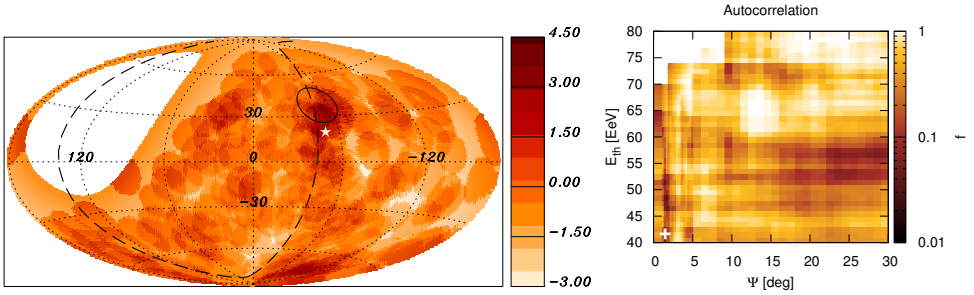

Figure 1: *Left*: map in galactic coordinates of the Li-Ma significances of excesses in 12°-radius windows for the events with $E \geq 54$ EeV. Also indicated are the Super-Galactic Plane (dashed line) and Centaurus A (white star). *Right*: Fraction f obtained in the autocorrelation of events versus ψ and $E_{\rm th}$, white cross indicating the minimum.

The autocorrelation of events The angular auto-correlation analysis is a simple method to test for self clustering in the arrival directions distribution. The principle is to count the number of pairs of events $N_p(\psi, E_{\rm th})$, above a given energy threshold $E_{\rm th}$ that are within a certain angular distance ψ. Using the full data set, we performed a scan in energy threshold from 40 EeV up to 80 EeV and in angle from 1° to 30° in which we compare the number of pairs $N_p(\psi, E_{\rm th})$ measured in data to the isotropic expectation. The result of the scan is shown in Figure 1 (right), where the fraction $f(\psi, E_{\rm th})$ of isotropic simulations that have a higher or equal number of pairs than the data is represented. The minimum of this fraction is found at $f_{\rm min} = 0.027$, for $\psi = 1.5^{\circ}$ and $E_{\rm th} = 42$ EeV, where 30 pairs are expected on average and 41 are observed. To quantify the significance of this minimum, we computed the penalized fraction P of isotropic data sets that lead to a lower or equal value of $f_{\rm min}$ under a similar scan. The resulting value $P \simeq 70$ % indicates that the auto-correlation function is compatible with isotropic expectations.

3. Search for cross-correlations with astrophysical sources

We investigate in this section the possible correlation between the arrival directions of cosmic rays with the position of nearby extra-galactic sources (for additional searches of correlation with

the Galactic and Super-galactic planes see [6]). We used three complementary catalogs that have an almost uniform coverage and that are complete above a given luminosity: namely the 2MRS catalog of galaxies [13], the Swift-BAT [14] X-ray catalog of AGNs, and a catalog of radio galaxies with jets compiled in [15].

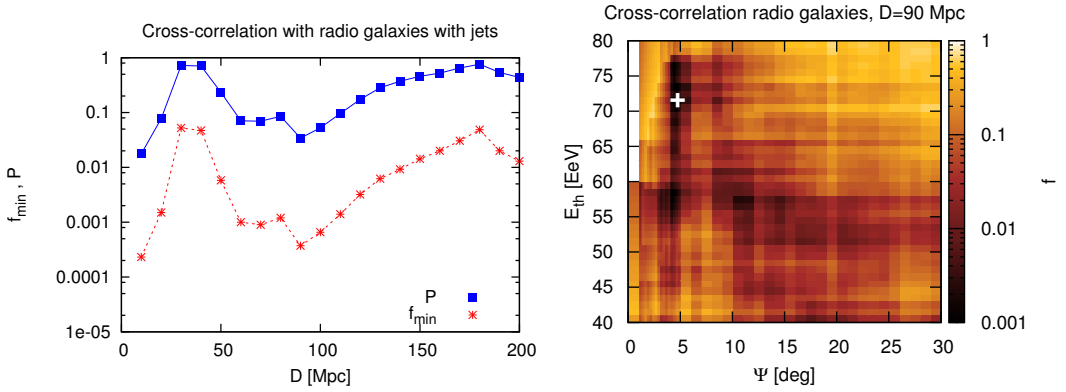

Figure 2: *Left*: Cross-correlation of events with the AGNs in the catalog of radio galaxies with jets. Values of $f_{\rm min}$ and P are shown as a function of the maximum distance D to the AGNs considered. *Right*: Results of the scan in ψ and $E_{\rm th}$ for the value $D = 90$ Mpc corresponding to the (second) minimum in the left plot.

The 2MRS catalog maps the local distribution of galaxies detected in the infrared domain, which could be associated with the location of gamma-ray bursts and newborn pulsars. The catalog is 97.6% complete above magnitudes brighter than $K_s = 11.75$ and contains more than 37,000 galaxies within 200 Mpc and about 16,000 galaxies within 100 Mpc.

The Swift-BAT catalog contains 1210 sources detected in X-rays after 70 months of operation, among which 705 are identified as AGNs and have a measured redshift. The catalog is complete for 90% of the sky above an X-ray flux of 13.4×10^{-12} erg cm^{-2} s^{-1} in the 14-195 keV range. This cut in flux selects 296 AGN-like galaxies within 200 Mpc and 160 within 100 Mpc.

The radio galaxy catalog that we use is a compilation from the 1.4 GHz NRAO VLA Sky Survey [16] and the 843 MHz Sydney University Molonglo Sky Survey [17] produced by Van Velzen et al. [15]. The catalog is quasi-complete for fluxes above 213 mJy at 1.4 GHz and 289 mJy at 843 MHz, and contains 205 radio galaxies with jets within 200 Mpc, and 56 within 100 Mpc. The overlap between the Swift-BAT and the radio galaxies catalog is only 5%, the majority of the Swift-BAT galaxies being of spiral type whereas the radio galaxies are mostly elliptical.

As a first approach, we use these catalogs in a cross-correlation analysis where all the objects with the above flux limits are selected. This selection corresponds to the assumption that all sources contribute to the cosmic ray flux in the proportion of their apparent luminosity. In a second approach, we select only the brightest sources from the catalogs by applying a cut in intrinsic luminosity which is motivated by the expectation that the maximum energy $E_{\rm max}$ achieved by the cosmic rays could be related to the intrinsic electromagnetic bolometric luminosity $\mathscr{L}$ of the object ($E^2_{\rm max} \propto \mathscr{L}$). In that case, we test the assumption that only the brightest sources can produce a cosmic ray flux above an energy threshold $E_{\rm th}$.

Cross-correlation with flux-limited catalogs The cross-correlation analysis is similar to the auto-correlation method, and consists in counting the number of pairs of a given angular separation

Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	$\mathscr{L}_{min}$ [erg/s]	f_{min}	$\mathscr{P}$
2MRS Galaxies	52	9	90	-	1.5×10^{-3}	24%
Swift AGNs	58	1	80	-	6×10^{-5}	6%
Radio galaxies	72	4.75	90	-	2×10^{-4}	8%
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	72	4.75	90	$10^{39.33}$	5.1×10^{-5}	11%
Centaurus A	58	15	-	-	2×10^{-4}	1.4%

Table 1: Summary of the parameters of the minima found in the cross-correlation analyses.

between cosmic ray events and objects in a sources catalog. To find an excess, we compare the number of pairs with the expectation of an isotropic simulation. We scan over the energy threshold $E_{\rm th}$ of the events from 40 EeV up to 80 EeV and in angular scale Ψ between 1° and 30°. For the sources in the catalogs, we impose a maximum distance cut D, that can vary from 10 Mpc up to 200 Mpc in 10 Mpc steps.

For each value of D, we compute the fraction $f(\psi, E_{\rm th})$ of isotropic simulations having an equal or higher number of pairs than the data, and search for its minimum $f_{\rm min}$. We calculate the associated post-trial probability P as the fraction of isotropic realizations that lead to a lower or equal value of $f_{\rm min}$ under a similar scan on $E_{\rm th}$ and Ψ.

The evolution of $f_{\rm min}$ and P as a function of the maximum distance D is shown in Figure 2 (left) for the radio galaxies catalog. The absolute minimum is $f_{\rm min} = 2\times10^{-4}$ with a penalized value of $P = 1.4\%$ obtained for a distance $D = 10$ Mpc. The only object in that distance range is Cen A , the closest radio galaxy located at 4.2 Mpc. As we discuss the correlation with Cen A in a separate section, we describe here only the second minimum of $f_{\rm min} = 4\times10^{-4}$ and $P = 3.4\%$ that occur for $D = 90$ Mpc. The result of the scan in energy and angular radius for $D = 90$ Mpc is shown in Figure 2 (right). The minimum (indicated by a white cross) corresponds to $E_{\rm th} = 72$ EeV and $\Psi = 4.75°$, where 13 pairs are observed in data and 3.2 are expected in average from isotropy. The penalized probability $\mathscr{P}$ of getting a lower or equal value of $P = 1.4\%$ (that is the absolute minimum of the scan) when repeating the same scan in distance D with isotropic samples is $\mathscr{P} = 8$ %.

The same analysis is applied for the 2MRS and Swift-BAT catalogs, and the results are summarized in table 1. The penalized probabilities $\mathscr{P}$ are of the order of a few percent, indicating that no significant excess is observed in this cross-correlation test.

Cross-correlation with bright AGNs We describe here the results of an additional scan on the minimum luminosity $\mathscr{L}_{\rm min}$ of the sources in the catalogs. The cross-correlation analysis was applied on the Swift-BAT AGNs where we used the luminosity $\mathscr{L}_{\rm X}$ measured in the X-ray band, and for the radio galaxies with the radio luminosity $\mathscr{L}_{\rm R}$ computed at 1.1 GHz. For Swift-BAT we scan from $\mathscr{L}_{\rm X} = 10^{42}$ erg/s up to 10^{44} erg/s, while for the radio galaxies we scan from $\mathscr{L}_{\rm R} = 10^{39}$ erg/s up to 10^{41} erg/s, considering three logarithmic steps per decade, for a total of 7 luminosity values in each case. These values are designed to cover most of the luminosity range of the AGNs that are present in the catalogs.

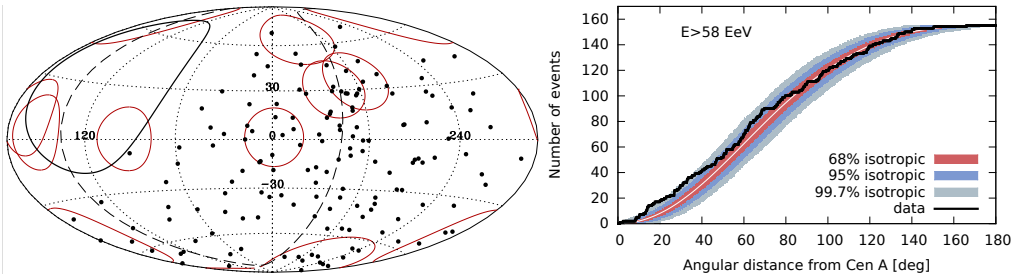

Figure 3: *Left*: Map in galactic coordinates showing the events (black dots) with $E \geq 58$ EeV together with the Swift AGNs brighter than 10^{44} erg/s and closer than 130 Mpc, indicated with circles of 18° radius. *Right*: cumulative number of events around the Cen A radio galaxy, for the threshold $E_{\rm th} = 58$ EeV, exploring the whole angular range.

The analysis procedure is similar to what was described in the previous section: we search for the minimum of the fraction $f(\psi, E_{\rm th})$ of isotropic simulations having an equal or higher number of pairs than the data, for each value of D and $\mathscr{L}_{\rm min}$. The resulting parameters that correspond to the minimum are included in table 1.

For Swift-BAT bright AGNs, the minimum $f_{\rm min} = 2 \times 10^{-6}$ is obtained for $D = 130$ Mpc and $\mathscr{L} > 10^{44}$ erg/s, with a threshold energy of $E_{\rm th} = 58$ EeV and an angular radius $\Psi = 18°$. For those parameters, 62 pairs are observed between 155 cosmic rays and 10 AGNs (with $\mathscr{L}_{\rm X} > \mathscr{L}_{\rm min}$) while 32.8 are expected from isotropy. A sky map is shown in Figure 3 (left) representing these events and AGNs in galactic coordinates. The penalized probability to find in isotropic simulations $f_{\rm min}$ values lower or equal than 2×10^{-6} under the same scan on $(\Psi, E_{\rm th}, \mathscr{L}_{\rm min}, D)$ is $\mathscr{P} \simeq 1.3\%$.

For the radio galaxies, two equivalent minima are found when scanning in luminosity, both for a maximum distance $D = 90$ Mpc. The first one is obtained for a luminosity $\mathscr{L}_{min} = 10^{39.33}$ erg/s, with ($E_{\rm th} = 72$ EeV, $\Psi = 4.75°$), and corresponds to a fraction $f_{\rm min} = 5.1 \times 10^{-5}$. For those parameters, 13 pairs are observed while 2.4 are expected from isotropy. The second minimum has $\mathscr{L}_{\rm min} = 10^{40}$ erg/s, for ($E_{\rm th} = 58$ EeV, $\Psi = 12°$), with a fraction $f_{\rm min} = 5.6 \times 10^{-5}$. The penalized probability corresponding to the first minimum is found to be $\mathscr{P} \simeq 11\%$.

The Cen A region At a distance of only 4 Mpc, Cen A is the closest radio-loud active galaxy, being a natural candidate source for the acceleration of high energy cosmic rays. We also note that the Centaurus cluster, which contains of a large number of galaxies, lies at a distance of 50 Mpc and is approximately in the same direction as Cen A. We thus searched for a correlation between the cosmic ray arrival directions and the location of Cen A, counting the number of events within an angular radius Ψ between 1° and 30° for an energy threshold $E_{\rm th}$ ranging from 40 EeV up to 80 EeV. The significance of a potential excess is evaluated by computing the fraction f of isotropic simulations that give a higher or equal number of events than the data.

The minimum of this fraction is found to be $f_{\rm min} = 2 \times 10^{-4}$ for $E_{\rm th} = 58$ EeV and $\Psi = 15°$, where 14 events are observed while 4.5 are expected. The right panel of Figure 3 shows the number of events with $E > 58$ EeV as a function of the angular distance from Cen A for the whole angular range, indicating also the 68, 95 and 99.7% intervals obtained with isotropic simulations. The penalized probability to find a smaller $f_{\rm min}$ value in isotropic simulations under the same scan is $\mathscr{P} \simeq 1.4\%$.

4. Discussion

The distribution of arrival directions of cosmic rays detected by the Pierre Auger Observatory in 10 years of operation has been studied by several complementary methods. An update of the fraction of events with $E > 53$ EeV correlating with AGNs from the VCV catalog has been performed, leading to a value of $(28.1^{+3.8}_{-3.6})$ %, which is only 2 standard deviations above the isotropic expectation of 21%.

We then searched for intrinsic anisotropies in the distribution of arrival directions of cosmic rays with energies above 40 EeV by computing the angular auto-correlation function and by looking at potential excesses in circular windows all across the exposed sky. Both tests give results that are compatible with isotropic expectations.

The cross-correlation with nearby (within 200 Mpc) sources from three complementary astrophysical catalogs has been performed, together with a specific analysis of the arrival directions around the Cen A radio galaxy. The results are summarized in table 1. The penalized probabilities $\mathscr{P}$ accounting for the scan on parameters are of the order of a few percent, and can reach the 1% level when selecting only the brightest AGNs of the Swift-BAT catalog or with the Cen A radio galaxy. We note that all minima, despite being not statistically significant, occur for a value of the maximum distance $D \simeq 80 - 90$ Mpc.

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