Search for anisotropies at the highest energies with Pierre Auger Observatory

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In this work, we used the data from Pierre Auger Observatory to study the distribution of arrival directions of Ultra-High Energy Cosmic Rays looking for anisotropy signals. In order to do that, we used the Monte Carlo method to simulate the isotropically-expected distribution, compared it with the one observed on the data from Auger, and quantified their differences. Still, we used astronomical catalogs in order to look for spatial correlations between regions with more events than expected by a confidence level larger than 3σ and active galactic nuclei. Finally, we studied the deflections experienced by the cosmic rays due to extragalactic magnetic fields through the Extragalactic Cosmic Ray Propagator, a package that tracks the path followed by the particles during their journey between its sources and the Earth under the influence of such fields. The results show that although the observed and expected distributions agree mostly, there are regions where they differ by more than 3σ threshold adopted by us in order to classify the regions as statistically significant, both with excesses or deficits. Moreover, we show the relevance of determining the composition of cosmic ray in order to study anisotropy in its arrival direction, since heavier nuclei are more much deflected than light ones.

I. INTRODUCTION

Cosmic rays are particles that travel through the interstellar medium with velocities very close to the speed of light and impinge the Earth’s atmosphere producing a cascade of secondary known as Extensive Air Shower (EAS) [1]. Above 10$^{18}$ eV they are called Ultra-High Energy Cosmic Rays (UHECR) [2]. Their origin, propagation, and features are currently one of the biggest open problems of astroparticle physics because their energies are thousands of times higher than the largest human-made accelerator, Large Hadron Collider (LHC) [3], has ever reached. Furthermore, their flux is very low: only 1 particle per year per square kilometer reaches the Earth’s atmosphere with an energy of 10$^{18}$ eV. The flux is even lower at 10$^{20}$ eV, only 1 particle per square kilometer per century [2].

Several models have been suggested in order to explain the physical mechanisms through which UHECR reach such enormous energies. The most popular ones are “top-down” and “bottom-up” models. The former are non-acceleration models and suggest that UHECR are originated on the decay of hypothetical supermassive particles of the Early Universe. On the other hand, the latter suggest that UHECR are accelerated at astrophysical sites by two possible mechanisms: diffusive shock waves or direct acceleration due to intense electromagnetic fields [4].

Within the study of the sources of UHECR, the Greisen-Zatsepin-Kuzmin effect [5, 6] (GZK effect, in honor of its founders) plays an important role: according to it, the Cosmic Microwave Background (CMG), originated in the early stages of the Universe, becomes opaque to protons with energies around 10$^{20}$ eV, which means that the UHECR energy spectrum should not extend above this threshold. These protons lose their energy mostly due to the photopion production. By the same mechanism, the sources of UHECR with energies around 10$^{18}$ eV are limited to a distance of 75 Mpc, since for larger distances they would lose their energy below this threshold.

Considering that UHECR are accelerated according to “bottom-up” models, Hillas [7] suggested that any astrophysical site where the particles might be accelerated must fulfill several conditions. Among them, the main one is: they must have a magnetic field (B) in order to keep the particles confined within it during the acceleration process [8]. Therefore, the size of the region (R) must be larger than the diameter of the orbit of the particle. These arguments are summarized in equation 1 [7, 8],

$$\frac{B}{\mu G} \left( \frac{R}{\text{kpc}} \right) > 2 \left( \frac{E}{10^{18} \text{eV}} \right) \frac{1}{Z\beta},$$

where $E$ is the energy of the particles, $Z$ is its atomic number and $\beta$ the ratio between the velocity of the magnetic scattering centers and the speed of light. These arguments allow one to restrict the search for the sources of UHECR to some astrophysical objects that are either large, or have an intense magnetic field, or both. Active Galactic Nuclei (AGN) are an example of astrophysical objects that fulfill the requirements to be a UHECR acceleration site.

In this work, we used the data from Pierre Auger Observatory [9, 10] to study the distribution of arrival directions of UHECR looking for pieces of evidence of anisotropy, relating them to astrophysical objects such as AGN. In addition, we incorporated the deflections experienced by the particles due to Extragalactic Magnetic Fields (EGMF) to the anisotropy analyses through simulations performed with the Extragalactic Cosmic Ray Propagator (EGCRProp) package [11, 12].

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This paper is organized as follows. In section II we present a brief description of the Pierre Auger Observatory, its detection techniques, and future prospects. In section III we describe the data used during the analyses presented in this work. In section IV we present the method used to perform the simulations of the distributions of arrival directions and the results of its analysis. In section V we present the analysis performed regarding the deflections experienced by the particles during its path to Earth and, finally, in section VI we present a brief summary of the work as well as our conclusions.

II. PIERRE AUGER OBSERVATORY

Located in Malargüe, Argentina, the Pierre Auger Observatory (Auger) [9, 10] is currently the largest facility on Earth intended to detect of UHECR. Collecting data since 2004, Auger is the result of an effort of more than 400 scientists among physicists and engineers from 15 countries. The observatory consists of a hybrid detector [10], since it employs two different techniques for the detection of UHECR: in the Surface Detector (SD) the lateral particle densities are sampled by 1,660 water-Cherenkov stations separated by 1,500 m in a hexagonal grid spread over an area of 3000 km$^2$ [13], and in the Fluorescence Detector (FD) the longitudinal light profile is measured by 27 large area telescopes located at four sites, Los Leones, Colihueco, Los Morados and Loma Amarilla [14], as one can see in figure 1. Their data are cross-calibrated, thus providing optimal data quality and a direct measurement of the shower energy, not depending on simulations.

A. THE FLUORESCENCE DETECTOR

By crossing the atmosphere with ultra-high energies, charged particles generated during the development of the EAS excite atmospheric nitrogen molecules causing an emission of ultraviolet radiation that is detected by the 27 fluorescence telescopes.

Each telescope has a 30° × 30° field of view and is composed by a spherical mirror of 13 m$^2$ of area, radius of curvature measuring 3.40 m and a camera formed by 440 Photomultiplier Tubes (PMT) organized in an array of 20 × 22 tubes that capture the focused light [14], as one can see in figure 2.

Unlike the SD, which has a duty cycle of approximately 100%, the current duty cycle of the FD is limited to low luminosity and good weather nights, which represents approximately 15% of its lifetime. On the other hand, the FD provides important measurements of the air showers, such as its longitudinal development and model-independent energy reconstruction. Moreover, their data are used for cross-checks with the SD data with high-quality hybrid events.

B. THE SURFACE DETECTOR

The tanks of the SD are responsible for the detection of the Cherenkov radiation induced by the passage of the ultrarelativistic particles through them. Each of the 1,660 tanks is composed by a unit of 3.6 m in diameter and 1.6 m in height filled with 12,000 ℓ of ultrapure water. In addition, they also have three 8 inch PMT looking downward, batteries and solar panels responsible for their maintenance [13], as one can see in figure 3. The Cherenkov light is converted to electronic pulses that are sent to a central data collection center synchronized by GPS.

As previously mentioned, the SD has a duty cycle of approximately 100%, thus providing an amount of data much larger than the FD. On the other hand, unlike the FD, the reconstructions of the SD depend on hadronic interaction models at energies much larger than the energies achieved by LHC [3].
C. THE PIERRE AUGER OBSERVATORY UPGRADE

Despite almost 15 years of data collection by the Pierre Auger Observatory and the extremely important results it has achieved, some questions still remain unanswered. The quest for the sources of the UHECR is still on-going, as is the full understanding of the origin of the observed suppression of their flux above about $3 \times 10^{19}$ eV. The study of the mass composition of the primaries is in this respect mandatory. A deeper insight in the hadronic interactions at these unprecedented energies is needed as well; the most up-to-date simulations of these interactions show in fact a deficit in the production of the muonic component of the extensive air showers produced by the primary particles with respect to the measured one [17]. In order to study these problems, the Pierre Auger Collaboration proposed in 2015 an upgrade of the observatory facilities, known as ‘AugerPrime’ [18]. Among the intended enhancements are the installation of smaller PMT in the water-Cherenkov detectors to avoid saturation at the highest energies, and of plastic scintillators detectors over the tanks to help in the determination of the composition at the highest energies, and, for the fluorescence detector, an extension of the telescopes duty cycle [18].

AugerPrime is the on-going upgrade of the Pierre Auger Observatory that will extend the experiment lifetime until 2025 as well as provide new information on UHECR. With the intended improvements on the current facilities and on the analyses techniques, AugerPrime will provide better data that will contribute to the elucidation of many questions that have been puzzling the community for years, such as the origins of these particles, issue that is addressed on this work.

D. EXPOSURE OF THE OBSERVATORY

As the observatory only covers part of the sky, it is very important to establish how its exposure is distributed over the sky in order to study the distribution of the arrival direction of UHECR. Since the Observatory operates continuously, its celestial exposure function is uni-

form in right ascension ($\alpha$) [19]. On the other hand, the observatory is located at the southern hemisphere, thus its exposure function depends strongly on the declination ($\delta$) where it is to be calculated. Equation 2 describes how the exposure of a ground-based cosmic ray experiment relates to $\delta$ and the experiment location [19],

$$\omega(\delta) \propto \alpha_{max} \sin(\delta) \sin(a_0) + \cos(\delta) \cos(a_0) \sin(\alpha_{max}),$$

where $a_0$ is the latitude of the observatory and $\alpha_{max}$ is a parameter given by equation 3,

$$\alpha_{max} = \begin{cases} 0 & \text{if } \xi > 1, \\ \pi & \text{if } \xi < -1, \\ \arccos(\xi) & \text{if } -1 \leq \xi \leq 1, \end{cases}$$

where $\xi$ is a different parameter given by equation 4,

$$\xi = \frac{\cos(\theta_{max}) - \sin(\delta) \sin(a_0)}{\cos(\delta) \cos(a_0)},$$

and $\theta_{max}$ is, in turn, the maximum zenith angle for which the reconstructions are fully efficient. In the case of Auger, $a_0 = -35.25^\circ$ and $\theta_{max} = 60^\circ$.

Figure 4 depicts the behavior of the relative exposure function of Auger (top panel) as well as the event detection distribution (bottom panel) as a function of $\delta$. As one can see, the relative exposure achieves its maximum value for $\delta \approx -90^\circ$, drops to approximately 0.7 for $-80^\circ < \delta < -50^\circ$ and goes to zero for $\delta \approx 30^\circ$. The event detection distribution derives from the exposure function and represents the isotropically-expected distribution of events. As one can see in the bottom panel of figure 4, it is symmetrically distributed around its maximum value achieved in $\delta \approx -30^\circ$, which, as expected, coincides with the location of Auger. As will be mentioned in the next sections, the event detection distribution is the basis for all the performed Monte Carlo simulations of the arrival directions.

III. DATASETS

During this work, we used three different datasets in order to compare and complement the results. Since they are all from Auger (as will be addressed later, they differ by the reconstruction technique employed in its reconstruction), we didn’t expect significant differences between the results obtained for each one and they were, in fact, very similar.

The first dataset (“Observer 1”) is composed by 110,410 events known as ‘Golden’ collected during the period between January 2004 and October 2016. In order to be classified as ‘Golden’, the event must trigger both FD and SD stations in an amount large enough to perform independent SD reconstructions [20]. The second dataset (“Observer 2”) is composed by all events detected and reconstructed by the SD during the period of January 2004
and December 2016, resulting in an integrated exposure of 51,763.67 km$^2$ sr yr and a much larger amount of data than “Observer 1”, more than three million events. Finally, the last dataset (“Herald”) is also composed by all the events detected by SD, however, the collection period is larger, between January 2004 and May 2017, and so is the integrated exposure, 53,757.63 km$^2$ sr yr, and the amount of data, approximately five million events. Moreover, the reconstruction technique employed in this dataset is different, as is described below.

The main difference between the first two datasets (“Observer” 1 and 2) and the last one (“Herald”) is the technique employed in their reconstruction. The former are reconstructed through the software ‘Offline’ [21, 22], and the latter is reconstructed through the ‘Central Data Acquisition System’ (CDAS) [23], which reconstructs only events from SD.

In order to avoid possible badly or non-reconstructed events, we eliminated the ones detected during periods of bad behavior of the observatory (known as ‘Bad Periods’) and the ones with zenith angles larger than 60°, since the reconstructions are fully efficient only below this threshold.

IV. MONTE CARLO SIMULATIONS OF THE PARTICLE’S ARRIVAL DIRECTIONS

There are many ways to study the distribution of UHECR over the sky and look for possible anisotropies in its arrival direction. In this work, we compare the event count distribution within bins of different sizes$^1$, 6°, 20° and 40°, for the datasets described in section III (observed distribution) with the isotropically-expected one (expected distribution).

In order to obtain the latter we performed Monte Carlo simulations of the particle’s arrival directions, declination (δ) and right ascension (α), through the following method: since the exposure of Auger is uniform in α, as described in section II.D, simulate it only required converting random numbers$^2$ to α. On the other hand, the exposure and, hence, the event detection distribution, depend strongly on δ where it is to be calculated, as one can see on figure 4, thus simulating it is little trickier. In this case, the random numbers were generated according to a probability density function represented by the event detection distribution, $\omega(\delta)\cos(\delta)$, and then converted to δ. The amount of simulated events is given by the dataset and the energy threshold to be analyzed, as shows table I. Moreover, the expected distributions considered in the analyses are the average of 1000 simulated datasets. In summary: supposing we want to perform the analysis on the data from “Observer 1” for energies above 40 EeV. In this case, we simulate 419 (see table I) events 1000 times, compute the average count of events within each bin and then compare it with the event count of the observed distribution bin by bin.

Finally, in order to represent the results, we defined a variable named significance (S) as the difference between the observed and expected event count normalized by the standard deviation from the simulation, thus positive (negative) values mean that the number of observed events is larger (smaller) than the expected. This value is calculated for every bin.

<table>
<thead>
<tr>
<th>Energy threshold (EeV)</th>
<th>Observer 1</th>
<th>Observer 2</th>
<th>Herald</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>110,410</td>
<td>3,981,716</td>
<td>5,782,394</td>
</tr>
<tr>
<td>10</td>
<td>13,127</td>
<td>14,012</td>
<td>14,809</td>
</tr>
<tr>
<td>40</td>
<td>419</td>
<td>522</td>
<td>509</td>
</tr>
<tr>
<td>60</td>
<td>97</td>
<td>119</td>
<td>113</td>
</tr>
<tr>
<td>90</td>
<td>19</td>
<td>24</td>
<td>19</td>
</tr>
<tr>
<td>110</td>
<td>4</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

1 The sizes of the bins were chosen so that we performed the analyses in small, medium and large scale and considering results recently published by the Pierre Auger Collaboration. In addition, to analyze the results at the highest energies, we had to use larger bins due to the low event count in this case.

2 The random number generator used during this work was ‘TRandom3’, which is based on the Mersenne Twister Generator and has a period of $10^{6000}$. 

Figure 4. Behavior of the celestial exposure function of the Pierre Auger Observatory. Top panel: Relative exposure as a function of the declination. The values were normalized by the maximum value encountered (1.8131). Bottom panel: Distribution of events as a function of the declination.
A. RESULTS

Figure 5 presents the significance maps obtained in the analysis of the “Observer 1” dataset for energy threshold in 10, 40, 60 and 90 EeV\(^3\). As one can see, it is a two-dimensional histogram at which the z-axis represents the calculated significance for each bin and the more yellow (blue) the bin, the greater the excess (deficit) of events. The same maps were performed for the other two datasets, “Observer 2” and “Herald”.

As one can see, most of the bins presented significance in the range \(-1 < S < 1\), which means that the observed and expected count differ by \pm 1\sigma, which we considered as not statistically significant enough to be considered as an anisotropy signal. However, a few bins presented values of \(S\) larger than \pm 3\sigma, what we considered as the threshold for the excess (deficit) to be considered as a potential anisotropy signal. We classified these regions (bins) as Regions Of Interest (ROI) and considering all datasets, we obtained a total number of 19 ROI, 18 of them presented excess of events and only one presented deficit, as one can see in table II, which presents the identifier of the ROI, its significance, equatorial coordinates, as well as the observed and expected counts (\pm the standard deviation).

Although there is a large number of ROI, many of them are located in regions where the exposure of the observatory is very low (see Fig. 4 and Table II) - ROI 10, 15 and 19 - and, hence, so are the expected and observed counts. Therefore, we neglected them in the following analyses. For example, ROI 10 has \(S = 5.27\), the greatest of all ROI, however, the number of expected and observed events are, respectively, 0.15 \pm 0.35 and 2.00, which makes it very difficult to distinguish whether this is a signal of anisotropy or a statistical fluctuation. On the other hand, some ROI presented interesting results that deserve to be highlighted. ROI 9, for example, has \(S = 3.58\) and both expected and observed counts are large enough so that we can consider it as an anisotropy signal. In addition, ROI 4 was the only one with \(S < 0\) and, moreover, it is located in a region of large exposure of the observatory. Therefore, it might be an evidence of the presence of some strong magnetic field that deflects particles that come from this direction.

B. SPATIAL CORRELATIONS BETWEEN REGIONS OF INTEREST ANDASTROPHYSICAL OBJECTS

In this section, we present the results of the search for spatial correlations performed in astronomical catalogs\(^3\) in order to associate the ROI to astrophysical objects, mostly AGN, as discussed in section I, that might be the sources of the observed discrepancies. The catalogs we based our analysis were the “Veron Catalog of Quasars and AGN, 13th Edition”\(^2\) (Veron) and “Swift BAT 60-Month Survey of Active Galactic Nuclei Catalog”\(^5\) (Swift BAT) since they are widely applied in anisotropy studies.

The “Veron Catalog of Quasars and AGN, 13th Edition”\(^2\) is a listing of 168,941 astrophysical objects of which 133,336 are quasars, 1,374 are BL Lacertae active nuclei and 34,231 are AGN. It provides information about the location of the object, redshift (\(z\)), absolute and rel-

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\(^3\) These values were chosen arbitrarily so that we analyzed all the energy range. In addition, energy threshold in X means that we only considered particles with energies larger than X.
Table II. Information about all ROI relative to the data set for which it presented the largest $S$. The error associated with the expected count is the standard deviation obtained by averaging of the 1000 simulations. ROI 1-4 were obtained performing the analysis with no energy cutoff, ROI 5-10 and 18-19 for energy threshold in 10 EeV, ROI 11-13, 40 EeV, ROI 14-16, 60 EeV and ROI 17, 90 EeV.

<table>
<thead>
<tr>
<th>ROI</th>
<th>Significance $(S)$</th>
<th>$\alpha(\circ)$</th>
<th>$\delta(\circ)$</th>
<th>Expected count</th>
<th>Observed count</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.12</td>
<td>66 - 72</td>
<td>84 S - 78 S</td>
<td>34.34 ± 5.97</td>
<td>53.00</td>
</tr>
<tr>
<td>2</td>
<td>5.13</td>
<td>18 - 24</td>
<td>24 N - 30 N</td>
<td>1.22 ± 1.13</td>
<td>7.00</td>
</tr>
<tr>
<td>3</td>
<td>3.31</td>
<td>228 - 234</td>
<td>24 N - 30 N</td>
<td>1.28 ± 1.12</td>
<td>5.00</td>
</tr>
<tr>
<td>4</td>
<td>-3.03</td>
<td>198 - 204</td>
<td>6 S - 0</td>
<td>113.36 ± 11.02</td>
<td>80.00</td>
</tr>
<tr>
<td>5</td>
<td>3.26</td>
<td>54 - 60</td>
<td>66 S - 60 S</td>
<td>10.65 ± 3.18</td>
<td>21.00</td>
</tr>
<tr>
<td>6</td>
<td>3.78</td>
<td>186 - 192</td>
<td>66 S - 60 S</td>
<td>10.50 ± 3.30</td>
<td>23.00</td>
</tr>
<tr>
<td>7</td>
<td>3.20</td>
<td>216 - 222</td>
<td>66 S - 60 S</td>
<td>10.45 ± 3.30</td>
<td>21.00</td>
</tr>
<tr>
<td>8</td>
<td>3.08</td>
<td>114-120</td>
<td>66 S - 60 S</td>
<td>11.27 ± 3.48</td>
<td>22.00</td>
</tr>
<tr>
<td>9</td>
<td>3.58</td>
<td>222 - 228</td>
<td>36 S - 30 S</td>
<td>18.49 ± 4.33</td>
<td>34.00</td>
</tr>
<tr>
<td>10</td>
<td>5.27</td>
<td>282 - 288</td>
<td>24 N - 30 N</td>
<td>0.15 ± 0.35</td>
<td>2.00</td>
</tr>
<tr>
<td>11</td>
<td>3.16</td>
<td>0 - 20</td>
<td>50 S - 30 S</td>
<td>7.27 ± 2.76</td>
<td>16.00</td>
</tr>
<tr>
<td>12</td>
<td>3.20</td>
<td>220 - 240</td>
<td>10 N - 30 N</td>
<td>1.73 ± 1.33</td>
<td>6.00</td>
</tr>
<tr>
<td>13</td>
<td>3.19</td>
<td>340 - 360</td>
<td>10 N - 30 N</td>
<td>1.72 ± 1.34</td>
<td>6.00</td>
</tr>
<tr>
<td>14</td>
<td>3.35</td>
<td>200 - 220</td>
<td>50 S - 30 S</td>
<td>1.64 ± 1.30</td>
<td>6.00</td>
</tr>
<tr>
<td>15</td>
<td>3.13</td>
<td>80 - 100</td>
<td>70 S - 50 S</td>
<td>0.96 ± 0.97</td>
<td>4.00</td>
</tr>
<tr>
<td>16</td>
<td>3.08</td>
<td>140 - 160</td>
<td>30 S - 10 S</td>
<td>1.37 ± 1.17</td>
<td>5.00</td>
</tr>
<tr>
<td>17</td>
<td>3.62</td>
<td>144 - 180</td>
<td>54 S - 18 S</td>
<td>1.16 ± 1.06</td>
<td>5.00</td>
</tr>
<tr>
<td>18</td>
<td>3.16</td>
<td>0 - 6</td>
<td>72 S - 66 S</td>
<td>9.48 ± 3.01</td>
<td>19.00</td>
</tr>
<tr>
<td>19</td>
<td>5.03</td>
<td>228 - 234</td>
<td>24 N - 30 N</td>
<td>0.14 ± 0.37</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Despite the low event count of the other ROI, they can not be disregarded since an increase in the data (as the one that will be provided by ‘AugerPrime’) can confirm their results.

V. PROPAGATION OF PARTICLES UNDER THE INFLUENCE OF MAGNETIC FIELDS

One of the main difficulties in the study of UHECR anisotropy is the deflection experienced by these particles due to EGMF present in the path between their sources and the terrestrial detectors. Since it is very hard to perform direct measurements, the structure of such fields is little known: its intensity is believed to be of the order of $10^{-9}$ G and they are likely composed by a uniform and a random component. The former can be an inheritance of the early stages of the universe. However, given the lack of experimental evidence for its existence, it can be neglected. Thus, the EGMF are composed mostly by the latter, whose source is still under debate: it can be either from ionized plasma emitted by galaxies and clusters of galaxies or AGN and other extremely energetic events [27]. Furthermore, the deflections depend on the composition of the particles, which is also an open problem in the study of UHECR: the most recent data collected by the Auger Collaboration show that the composition of primary cosmic rays is getting lighter approaching few $10^{18}$ eV, becoming then increasingly heavier as the energies increase [18].

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4 Both ROI 4 and 17 were not considered in this analysis since the former presented deficit of events instead excess and the latter is very wide, so that we found a quite large number of coincidences, and thus it makes little sense to point any individual object as a potential source. Furthermore, ROI 10, 15 and 19 were neglected due to the their low exposure.

5 Hopefully ‘AugerPrime’ will be able to solve this issue.
As one might have noticed, the composition of the UHECR was neglected in the analyses carried out so far. In order to handle it, in this section, we present the results obtained regarding the deflection experienced by such particles due to EGMF as a function of its composition and energies. As will be mentioned below, we used the EGCRProp package [11, 12] to perform the tracking of the paths followed by the particles in its journey between its sources and the Earth.

A. CHARGED PARTICLES IN MAGNETIC FIELDS

Considering a particle of rest mass $m_0$ and charge $Ze$ moving under the influence of a uniform stationary magnetic field ($\vec{B}$) and a negligible electric field with velocity $\vec{v}(t)$ and trajectory $\vec{r}(t)$, its equation of motion is given by 5 [28] (written in the Gaussian-cgs units),

$$\frac{d\vec{p}}{dt} = Z e \frac{\vec{v}}{c} \times \vec{B},$$

that give us the following relation [28],

$$\frac{d\vec{v}}{dt} = \vec{v} \times \vec{\omega}_B,$$

where $\vec{\omega}_B = (Ze/\gamma m_0 c) \vec{B}$ is the cyclotron frequency of a particle with rest mass $m_0$ and Lorentz factor $\gamma$ [11]. The component of $\vec{v}(t)$ parallel to $\vec{B}$ ($\vec{v}_\parallel$) is uniform, the perpendicular one ($\vec{v}_\perp$) is circular and, thus, the trajectory given by 6 is helicoidal and its solution is given by 7 [28],

$$\vec{v}(t) = \omega_B L_R (\hat{\epsilon}_1 - i \hat{\epsilon}_2) e^{-i \omega_B t} + \vec{v}_\parallel \hat{\epsilon}_3,$$

where $i$ is the imaginary unit, $\hat{\epsilon}_3$ is a unitary vector parallel to the field, $\hat{\epsilon}_1$ and $\hat{\epsilon}_2$ are unitary vectors perpendicular to it and $L_R$ is the Larmour radius of the particle. Finally, the equation for the trajectory of the particle is given by 8 [28],

$$\vec{r}(t) = \vec{r}_0 + i L_R (\hat{\epsilon}_1 - i \hat{\epsilon}_2) e^{-i \omega_B t} + \vec{v}_\parallel \hat{\epsilon}_3,$$

where $\vec{r}_0$ is the initial position of the particle.

### B. THE EGCRPROP

The EGCRProp [11, 12] package is a software that tracks the path followed by the particles under the influence of a magnetic field of cellular structure with coherence length $l_{coh} = 1$ Mpc and is composed by two codes: the propagator itself and a tensorial magnetic field generator. The universe is modeled as a cube of volume $(170\text{ Mpc})^3$ composed by cells of diameter $l_{coh}$ within which the magnetic field has intensity $B = 1 \text{ nG}$ and random orientations (given by the tensorial magnetic field generator). At $t = 0$ the particle begins its motion from the center of the universe and at each time step its position and velocities are computed through the increment of equations 7 and 8 and so is its energy losses due to the interaction with photons of the CMB [11]. Before running the program we can preset parameters as the composition of the particles, its initial energies, distance to be traveled, propagation mode, integration method, timescale, among others. The EGCRProp and its documentation are available to download at [12].

### C. RESULTS

Figure 6 shows the average deflection $\Delta$ experienced by particles of different composition as a function of the distance traveled by them and their energy. The energy thresholds are the same as in the previous analyses, i.e, 10, 40, 60 and 90 EeV. Each point of the graphs is the average deflection of 500 particles. The method of integration adopted was the Boris’ method with an integration step of 0.001. In addition, we used the backtracking mode and neglected the energy losses. By neglecting the

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6 There are two modes available: forward and backtracking. In the former, the particle starts its journey in the center of the universe ($d = 0$) and travels until the stopping distance losing energy. In the latter, the particles depart from the stopping distance and travel until $d = 0$ gaining energy.

7 In this context, deflection is the angle between the vectors pointing to the initial and final directions.
energy ‘gains’ (as we used the backtracking mode mode), \( \Delta \) represents a superior limit to the real deflection since the larger the energy, the smaller is \( \Delta \).

As one can see in figure 6, \( \Delta \) depends strongly on the composition of the particle, so that heavier particles present larger deflections. For example, iron nuclei of energy 10 EeV traveling 75 Mpc have \( \Delta < (111.69 \pm 35.65)^\circ \) and a proton with the same energy travelling the same distance has \( \Delta < (78.72 \pm 37.35)^\circ \). In addition, as previously mentioned, the greater the energy, the smaller the deflection so that a proton with 90 EeV travelling 75 Mpc has \( \Delta < (12.26 \pm 4.30)^\circ \), which is significantly smaller than the \( \Delta < (78.72 \pm 37.35)^\circ \) presented by a proton of 10 EeV. Regarding the traveled distance, \( \Delta \) raises together with it until a seeming ‘plateau’ that is different for different compositions.

In summary, this analysis makes clear the relevance of a precise determination of the composition of the UHECR in order to study anisotropy in the arrival directions of such particles. At energies of the order of 10 EeV, for example, the deflections are substantially large for almost every distance and composition, from proton up to iron nuclei. On the other hand, as the energy increases, so does the difference between the average deflection experienced by different compositions. Therefore, the search for spatial correlations between excesses and astrophysical objects, as the one performed in section IV.B, depends strongly on the composition of the primary particle. In this way, if we consider the particles as mostly iron nuclei it is very unlikely that a correlation between an excess and an object is, in fact, real, since for such particles the deflections are extremely large even at the highest energies. However, if the particles are mostly proton, the probability of a real correlation is much larger, since at the highest energies the deflections of such particles are quite small even for large traveled distances (\( \approx 10^5 \), see Fig. 6).

In order to incorporate the deflections suffered by the particles at the analysis performed in section IV.B, we performed a new reading of the catalogs considering the results presented above. In this sense, we expanded the size of the bins at which the excesses were found (in section IV.B) by a factor equals \( \Delta \) for the composition and distance considered, as is shown in figure 7. Then, we performed a new search for correlations considering the new bins. Figure 8 shows the results of this analysis. The graphs contain the cumulative number of objects found in all the 14 ROI as a function of the distance traveled by the particles and the same energy thresholds considered earlier. As one can see, the number of coincidences increases approximately linearly and is larger for heavier compositions (and, hence, deflections). In addition, it confirms the above statements, i.e., that for heavier compositions an analysis of spatial correlations is almost impossible whereas it is possible for lighter ones, especially at high energies. However, the larger the energies the smaller is the available statistics and, hence, so is the statistical confidence of the results. In this sense, the ‘AugerPrime’ is of great importance since it will provide us more data at such energies.
VI. SUMMARY AND CONCLUSIONS

In this work we studied the distribution of UHECR over the part of the sky covered by the Pierre Auger Observatory [9, 10] looking for pieces of evidence of anisotropy in its arrival directions through the comparison of the observed (at Auger data) and the isotropically-expected (obtained through Monte Carlo simulations) distributions. In addition, we performed a search for spatial correlations between regions that presented excesses in the previous analysis and astrophysical objects present at the Veron [24] and Swift BAT [25] catalogs that have $z < 0.018$, given the GZK cutoff [5, 6]. Finally, we analyzed the deflections experienced by UHECR due to EGMF and the influence it has on the previous analysis.

The results show that although the observed and expected distributions agree in most part of the sky, there are regions where they differ by more than $3\sigma$ (that we name ROI), most part of them located in regions of small exposure of Auger, both positive and negative, i.e, there are both excesses and deficits of events, with a predominance of the former. Still, we found 49 astrophysical objects within these regions that might be the sources of the observed discrepancies. The AGN Centaurus A, which is widely pointed as a possible source of UHECR, is among them, showing that our results are in line with the results recently published.

Moreover, considering the average deflection of the particles due to the EGMF we conclude that for heavier compositions it is very unlikely that a correspondence between an excess and an object be real, since such particles present very large deflections whereas for lighter nuclei it is reasonable to state the opposite, especially for higher energies and smaller distances. Finally, it is important to highlight that ‘AugerPrime’ will allow us to improve our results since more data at the highest energies will be available.

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