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Search for energy dependent patterns in the arrival direction of cosmic rays at the Pierre Auger Observatory

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Energy-dependent patterns in the arrival directions of cosmic rays are expected from deflections in galactic and extragalactic magnetic fields. We report on searches for such patterns in the data of the surface detector of the Pierre Auger Observatory at energies above $E = 5\,\mathrm{EeV}$ in regions within approximately 15° around events with energy $E > 60\,\mathrm{EeV}$. No significant patterns are found with this analysis which can be used to constrain parameters in propagation scenarios.

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1. Introduction

The sources of ultra-high energy cosmic rays (UHECR) have not been identified so far, presumably because of the deflection of the charged cosmic rays in the galactic and extragalactic magnetic fields. However, from such deflections the distribution of UHECRs arrival directions may show energy-dependent patterns. In particular, a circular 'blurring' of the sources is expected from deflection in turbulent magnetic fields, while energy-dependent linear structures are expected from deflection in coherent magnetic fields. To search for such patterns in the data collected with the Pierre Auger Observatory [1], we investigate the local Regions Of Interest (ROI) around cosmic rays with $E \geq 60\,\mathrm{EeV}$. We analyzed the cosmic rays with energies above $E = 5$ EeV arriving within an angular separation of $0.25\,\mathrm{rad}$ using two independent methods [2]. In one method we study energy-energy correlations between pairs of cosmic rays depending on their angular separation from the center of the region. This method is sensitive to the circular patterns expected from particle deflection in turbulent magnetic fields [3, 4]. In the second method we decompose the directional energy distribution of the cosmic rays along its principal axes. This method is sensitive to clusters of cosmic rays as well as to linear patterns expected from deflections in coherent magnetic fields [5, 6].

2. Methods

2.1 Energy-Energy Correlations

The Energy-energy correlation Ω_{ij} is calculated for every pair of UHECRs ij within a ROI using

$$\Omega_{ij} = \frac{(E_i - \langle E(\alpha_i)\rangle)\,(E_j - \langle E(\alpha_j)\rangle)}{E_i\,E_j} \tag{2.1}$$

where E_i is the energy of the UHECR i with the angular separation α_i to the center of the ROI and $\langle E_i(\alpha_i)\rangle$ is the average energy of all UHECRs at the angular separation α_i from the center of the ROI. A pair of cosmic rays ij can contribute positively or negatively to the distribution of Ω_{ij}. If one particle has an energy above the corresponding average energy and the other below the corresponding average energy, the contribution is negative. A pair with both energies being below average as well as a pair with both being above average contribute positively. If there is a pattern in the energy distribution there are more positive correlations than expected from isotropically distributed cosmic rays.

2.2 Principal Axes

The system of principal axes of the energy distribution $\vec{n}_{k=1,2,3}$ is calculated by successive maximization of the quantity

$$T_k = \max_{\vec{n}_k} \left(\frac{\sum_i |\omega_i^{-1}\, \vec{p}_i \cdot \vec{n}_k|}{\sum_i |\omega_i^{-1}\, \vec{p}_i|} \right) \tag{2.2}$$

with respect to the axes $\vec{n}_k$ starting with $k = 1$. Here $\vec{p}_i$ is the momentum and ω_i the exposure of the detector [7] in the direction of particle i. The resulting values of $T_{k=1,2,3}$ quantify the strength of the collimation of the particle momenta along each of the three axes $\vec{n}_{k=1,2,3}$ of the principal system.

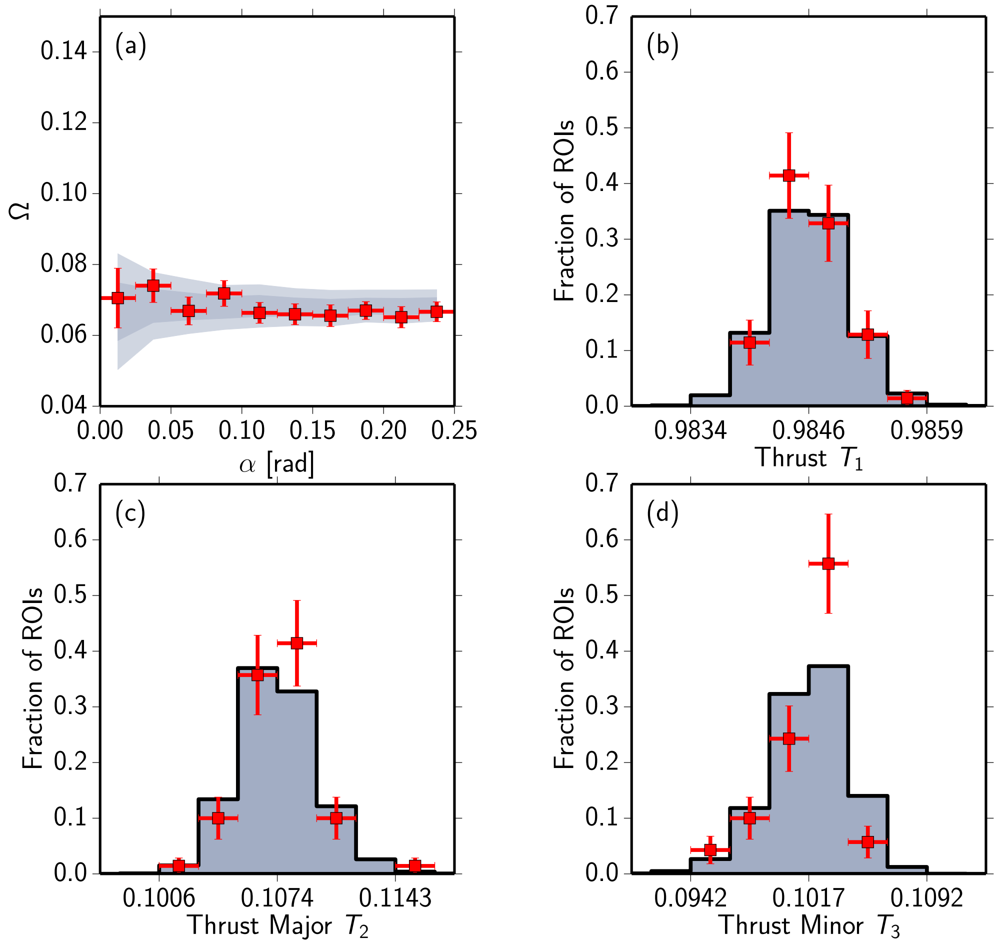

Figure 1: Measurement of the **(a)** energy-energy correlation Ω and **(b-d)** observables $T_{1,2,3}$ with the Pierre Auger Observatory (red squares and error bars). The measurements are compared to distributions without patterns in the arrival directions of UHECRs (filled distributions).

The first principal axis $\vec{n}_1$ is the radial unit vector $\vec{e}_r$ pointing to the local barycenter of the energy distribution. The T_1 value is thus a measure for the energy-weighted strength of clustering of the events. It is $T_1 = 1$ for no dispersion of the particles in the region, whereas for an isotropic distribution of UHECRs in a region the expectation value is determined by the size of the region [6].

The second and third principal axes $\vec{n}_2$ and $\vec{n}_3$ can be written as linear combination of the unit vectors $\vec{e}_\phi$ and $\vec{e}_\theta$. The T_2 value becomes maximal if $\vec{n}_2$ is aligned with a linear distribution of UHECR arrival directions and can be thus used as a generalized multiplet analysis. It thus points along threadlike structures in the energy distribution of UHECRs. As the $\vec{n}_2$ axis is chosen perpendicular to $\vec{n}_1$ and $\vec{n}_2$ it has no additional physical meaning. However, the T_3 value contains information as it denotes the collimation strength perpendicular to the $\vec{n}_2$ axis.

3. Results

We measured the EEC and $T_{1,2,3}$ distributions using 30,664 events recorded with the surface detector of the Pierre Auger Observatory above 5 EeV. For the selected events we further required that the zenith angle of the events is smaller than 60° and that the detector stations surrounding the station with the highest signal are active [8] to obtain a sample with minimum potential biases. Of the selected events, 70 have an energy $E \geq 60\,\mathrm{EeV}$ and are at least 0.25 rad inside the field of view of the Pierre Auger Observatory. These events mark the ROIs used in this analysis.

In Figure 1 the distributions of the EEC and the $T_{1,2,3}$ observables are shown together with the distributions expected from isotropic arrival directions of UHECRs. The measured distributions of all four observables reveal no local patterns in the arrival directions of UHECRs. The goodness-of-fit of the measurements compared to expected distributions without structure in the arrival directions of UHECRs using a χ^2 test, yields p-values which are all above $p = 0.2$ except for the T_3 distribution with $p(T_3) = 0.01$. However, this low p-value results from a lack of signal-like regions in the data which are expected to broaden the distribution, and thus does not indicate significant patterns.

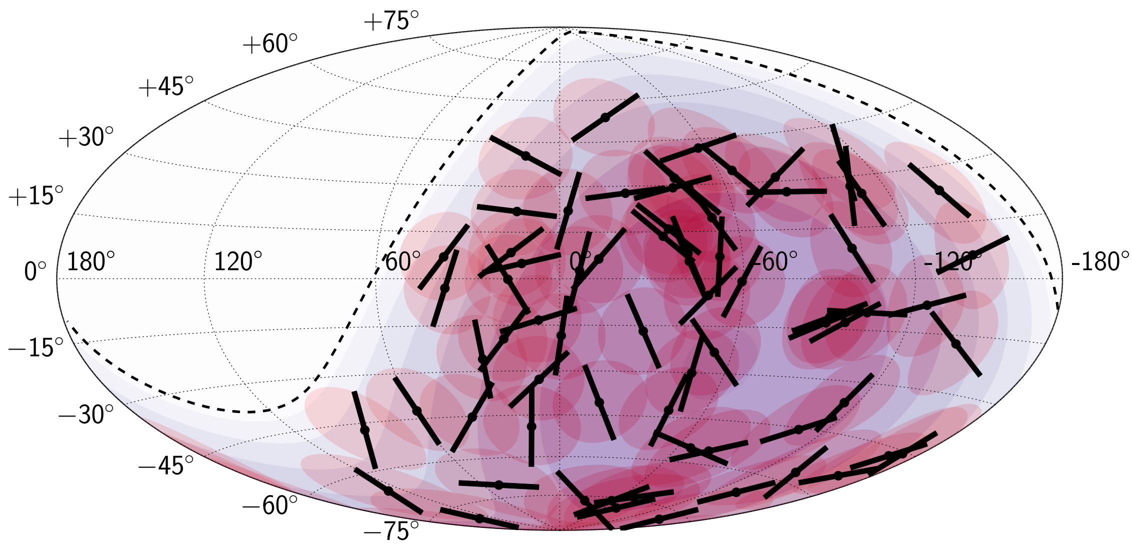

Figure 2: Map of principal axes of the directional energy distribution using a Hammer projection and galactic coordinates. The red shaded areas represent the regions of interest. Black lines denote the second principal axes $\vec{n}_2$ and black dots mark the positions of axes $\vec{n}_1$. The blue shading indicates the exposure of the Pierre Auger Observatory; the dashed line marks the extent of its field of view.

In addition to the scalar distributions, the direction of the second principal axes $\vec{n}_2$ can be displayed as the map shown in figure 2. If the axes are non-trivial, this map displays the directions of deflection of UEHCR in coherent cosmic magnetic fields. In simulation studies it was shown that the distribution of principal axes can contain information, even though the $T_{1,2,3}$ scalar values are compatible with isotropy [6]. We tested the reproducibility of the axes in subsets of the data by splitting the dataset into 12 independent subsets by chance and analyzing the variance of the directions in the subsets. We found no reproducibility of the axes in this analysis.

4. Discussion and Conclusions

The non observation of significant patterns can be used to exclude all scenarios that predict otherwise. To illustrate the required procedure we simulated a simple model for extragalactic propagation of protons based on parameterizations as implemented in version 1.2 of the PARSEC software [9]. In particular we assume here, that the UHECRs originate from isotropically distributed point sources with equal luminosity and that the root-mean-square of the deflections of UHECRs with energies E from a source in distance D can be parametrized as $\delta_{\mathrm{RMS}} = C_{\mathrm{E}} \frac{\sqrt{D}}{E}$. The calculations further account for energy losses of the UHECRs from interaction with extragalactic-photon backgrounds, effects from the expansion of the universe, and the deflection in the galactic magnetic field using the model proposed by Jansson and Farrar [10, 11].

We scanned the density of point sources and the strength of the deflection in the extragalactic magnetic field C_{E} in this scenario and derived a combined limit on both parameters using the CL_S method [12]. Within this simplified scenario, we found that the deflection in the extragalactic magnetic field has to be larger than $C_{\mathrm{E}} = 10 - 120^\circ\,\mathrm{Mpc}^{-1/2}\,\mathrm{EeV}$ for source densities smaller than $10^{-3}\,\mathrm{Mpc}^{-3}$. For protons with an energy $E = 10\,\mathrm{EeV}$ from a source at $16\,\mathrm{Mpc}$ this translates to a required strength of the deflection in extragalactic space of more than 4° if the source density is smaller than $10^{-3}\,\mathrm{Mpc}^{-3}$ and more than 25° if the source density is smaller than $10^{-4}\,\mathrm{Mpc}^{-3}$.

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