Search for energy-position correlated multiplets in Pierre Auger Observatory data

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Abstract: We present the results of an analysis of data recorded at the Pierre Auger Observatory in which we search for groups of directionally-aligned events (or ‘multiplets’) which exhibit a correlation between arrival direction and the inverse of the energy. These signatures are expected from sets of events coming from the same source after having been deflected by intervening coherent magnetic fields. We here report the largest multiplets found in the data and compute the probability that they arise by chance from an isotropic distribution of events. There is no statistically significant evidence for the presence of multiplets arising from magnetic deflections in the present data.

Keywords: Pierre Auger Observatory, ultra-high energy cosmic rays, magnetic fields, multiplets.

1 Introduction

The identification of the sources of cosmic rays is greatly complicated by the fact that cosmic rays traverse magnetic fields as they propagate from their sources to Earth. However, the deflections caused by magnetic fields are expected to be inversely proportional to the energy of the cosmic rays. Therefore, it may be possible to identify several cosmic ray events from the same source by looking for spatial alignments in their arrival directions and large correlations between the directions and the inverse of the energy. The identification of these kind of multiplets would not only allow for the accurate location of the direction of the source, but would also provide a measurement of the integral of the component of the magnetic field orthogonal to the trajectory of the cosmic rays.

Cosmic rays are deflected by galactic and extragalactic magnetic fields. The strength of extragalactic fields is not well known, and the importance of their effect is a matter of debate [1, 2, 3]. In this study, we focus on the effect of the galactic field. The galactic field is also poorly constrained, although there are considerable efforts underway to provide measurements of its amplitude and orientation [4, 5, 6]. This field is usually described as the superposition of a large-scale regular component and a turbulent one. The regular component has a few $\mu$G strength and is coherent on scales of a few kpc with a structure related to the spiral arms of the galactic disk. The deflection of cosmic rays with energy $E$ and charge $Z$ by the regular component of the magnetic field $B$ after traversing a distance $L$ is given by

$$
\delta \simeq 16^\circ \frac{20 \text{ EeV}}{E/Z} \left| \int_0^L \frac{dl}{3 \text{ kpc}} \times \frac{B}{2 \mu\text{G}} \right| .
$$

(1)

This is the predominant deflection because, although the turbulent component has a root mean square amplitude of $B_{\text{rms}} \simeq (1 - 2)B_{\text{reg}}$, it has a much smaller coherence length (typically $L_c \simeq 50$-100 pc) [7, 8], leading to a smaller deflection,

$$
\delta_{\text{rms}} \simeq 1.5^\circ \frac{20 \text{ EeV}}{E/Z} \frac{B_{\text{rms}}}{3 \mu\text{G}} \sqrt{\frac{L}{1 \text{kpc}}} \sqrt{\frac{L_c}{50 \text{pc}}}.
$$

(2)

In this study, we perform a search for correlated multiplets in the data set of events with energy above 20 EeV recorded at the Pierre Auger Observatory. This analysis relies on the acceleration at the source of at least one abundant light component. Due to the magnitude of the magnetic fields involved, heavy nuclei at these energies would appear spread over a very large region of the sky, probing regions with different amplitudes and directions of the magnetic field, and hence losing their alignment and correlation with the inverse of energy.

1. To detect several events from the same source, the sources of cosmic rays should be steady, in the sense that the lifetime of the source is larger than the difference in the time delays due to the propagation in the intervening magnetic fields for the energies considered. Moreover, magnetic fields should also be steady in the same sense so that cosmic rays traverse approximately the same fields.
2 The Pierre Auger Observatory and the data set

The Pierre Auger Observatory, located in Malargüe, Argentina, at 1400 m a.s.l., is the largest air shower array in the world and its main purpose is to measure ultra-high energy cosmic rays (energy \( E > 10^{18} \) eV \( \equiv 1 \) EeV). It consists of a surface array of 1660 water Cherenkov stations. The surface array is arranged in an equilateral triangular grid with 1500 m spacing, covering an area of approximately 3000 km\(^2\) [9]. The array is overlooked by 27 telescopes at four sites [10] which constitute the fluorescence detector. The surface and air fluorescence detectors are designed to perform complementary measurements of air showers created by cosmic rays. The surface array is used to observe the lateral distribution of the air shower particles at ground level, while the fluorescence telescopes are used to record the longitudinal development of the shower as it moves through the atmosphere.

The data used for this analysis are 1509 events with \( E > 20 \) EeV and zenith angles smaller than 60° recorded by the surface detector array from 1st January 2004 to 31st December 2010. The events are required to have at least five active detectors surrounding the station with the highest signal, and the reconstructed core must be inside an active equilateral triangle of stations [11]. The angular resolution, defined as the 68\(^{th}\) percentile of the distribution of opening angles between the true and reconstructed directions of simulated events, is better than 0.9° for events that trigger at least six surface detectors (\( E > 10 \) EeV) [12]. The absolute energy scale, given by the fluorescence calibration, has a systematic uncertainty of 22% and the energy resolution is about 15% [13].

3 Method for searching multiplets

If the magnetic deflections are small, it is a good approximation to consider a linear relation between the cosmic ray observed arrival directions \( \bar{\theta} \) and the inverse of the energy \( E \),

\[
\bar{\theta} = \bar{\theta}_s + \frac{Ze}{E} \int_0^L d\bar{L} \times \bar{B} \approx \bar{\theta}_s + \bar{D}(\bar{\theta}_s),
\]

where \( \bar{\theta}_s \) denotes the actual source direction, and \( \bar{D}(\bar{\theta}_s) \) will be called the deflection power\(^2\). In the case of proton sources, departures from the linear approximation are relevant for energies below 20 EeV for typical galactic magnetic field models [14].

In order to identify sets of events coming from the same source, the main requirement will be that they appear aligned in the sky and have a high value of the correlation coefficient between \( \theta \) and \( 1/E \). We will further require that the multiplets contain at least one event\(^3\) with energy above 45 EeV and that the multiplets do not extend more than 20° in the sky.

To compute the correlation coefficient for a given subset of \( N \) nearby events, we first identify the axis along which the correlation is maximal. For this we initially use an arbitrary coordinate system \((x, y)\) in the tangent plane to the celestial sphere (centered in the average direction to the events) and compute the covariances \( \text{Cov}(x, 1/E) = \frac{1}{N} \sum_{i=1}^{N} (x_i - \langle x \rangle)(1/E_i - 1/(1/E)) \) and \( \text{Cov}(y, 1/E) \). We then rotate the coordinates to a system \((u, w)\) in which \( \text{Cov}(w, 1/E) = 0 \), and hence \( \text{Cov}(u, 1/E) \) is maximal. This corresponds to a rotation angle between the \( u \) and \( x \) axes given by

\[
\alpha = \arctan \left( \frac{\text{Cov}(y, 1/E)}{\text{Cov}(x, 1/E)} \right).
\]

The correlation between \( u \) and \( 1/E \) is measured through the correlation coefficient

\[
C(u, 1/E) = \frac{\text{Cov}(u, 1/E)}{\sqrt{\text{Var}(u)\text{Var}(1/E)}},
\]

where the variances are given by \( \text{Var}(x) = \langle (x - \langle x \rangle)^2 \rangle \).

A given set of events will be identified as a correlated multiplet when \( C(u, 1/E) > C_{\text{min}} \) and when the spread in the transverse direction \( w \) is small, \( W = \max(|w_i - \langle w \rangle|) < W_{\text{max}} \). The values for \( C_{\text{min}} \) and \( W_{\text{max}} \) were chosen as a compromise between maximizing the signal from a true source and minimizing the background arising from chance alignments. We performed numerical simulations of sets of events from randomly-located extragalactic sources. In these simulations, protons were propagated through a bisymmetric magnetic field with even symmetry (BSS-S) [15, 16] and the effect of the turbulent magnetic field included by simply adding a random deflection with root mean square amplitude \( \delta_{\text{rms}} = 1.5^\circ(20 \) EeV/\( E)) \). We considered one hundred extragalactic sources located at random directions and simulated sets of \( N \) events with energies following an \( E^{-2} \) spectrum at the source and adding random gaussian uncertainties in the angular directions and energies to account for the experimental resolution. As an example we show in Figure 1 (left panel) the resulting distribution of \( W \) for multiplets of 14 events. The significance of a given multiplet can be quantified by computing the fraction of isotropic simulations in which a multiplet with the same or larger multiplicity and passing the same cuts appears by chance. We note that when reducing \( W_{\text{max}} \), some of the events of the multiplets will be missed and their multiplicity will be reduced. However, the significance of a smaller multiplet passing a tighter bound on \( W_{\text{max}} \) can

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\(^2\) The deflection power will be given in units of \( 1^\circ \) 100 EeV, which is \( \approx 1.9 \) e \( \mu \)G kpc.

\(^3\) Note that the energy of the most energetic event of a set of 10 events with \( E > 20 \) EeV from a source with spectral index \( s = 2.5 \) is larger than 45 EeV with a probability of 97% (for a spectral index \( s = 3 \) this probability is \( \approx 90\% \)).
be larger than the significance of the complete multiplet
with a looser $W_{\text{max}}$ cut. It turns out that the largest mean
significance for the simulated sources appears when a
cut $W_{\text{max}} \simeq 1.5^\circ$ is applied. In the case of 14-plets, in
50% of the simulations all the events pass this cut and the
multiplet will be reconstructed as a 14-plet, while in 38%
of the cases one event is lost and in 11% of the cases two
events are lost. The angular scale of $1.5^\circ$ provides in fact
a reasonable cut which accounts for the angular resolution
and the mean value of the turbulent field deflections.

A similar analysis can be performed to fix the cut on
the correlation coefficient $C_{\text{min}}$. The distribution of
$C(u, 1/E)$ for the simulated 14-plets is shown in Figure 1
(right panel). The largest mean significance is attained now
for values of $C_{\text{min}}$ in the range from 0.85 to 0.9, depending
on the multiplicity considered. For a cut $C_{\text{min}} = 0.9,$ in
57% of simulations with 14 events all events pass the
cuts, in 12% of the simulations one event is lost and in
11% of them two events are lost. We will then fix in the
following $W_{\text{max}} = 1.5^\circ$ and $C_{\text{min}} = 0.9.$ We note that the
choice of the optimal cut slightly depends on the galactic
magnetic field model considered in the simulations and on
the modeling of the turbulent field deflections.

When a correlated multiplet is identified it is possible to
reconstruct the position of its potential source $(u_s, 0)$ (in the
$u-w$ coordinate system) and estimate the deflection power
$D$ by performing a linear fit to the relation

$$ u = u_s + \frac{D}{E}. \quad (6) $$

### 4 Results

A search for correlated multiplets was performed in the
Pierre Auger Observatory data with events with energies
above 20 EeV. The largest multiplet found was one 12-plet. The probability that it appears by chance from
an isotropic distribution of events is $6\%$. Therefore, there is
no significant evidence for the presence of correlated mul-
tiplets arising from magnetic deflections in the present data
set. We will continue analyzing future data and check if
some of the observed multiplets grow significantly or if
some new large multiplets appear.

5 Conclusions

We performed a search for energy-position correlated mul-
tiplets in the data collected by the Pierre Auger Observatory
with energy above 20 EeV. The largest multiplet found was
one 12-plet. The probability that it appears by chance from
an isotropic distribution of events is $6\%$. Therefore, there is
no significant evidence for the presence of correlated mul-
tiplets arising from magnetic deflections in the present data
set. We will continue analyzing future data and check if
some of the observed multiplets grow significantly or if
some new large multiplets appear.

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4. Decaplet II in Table 1 consists of three dependent sets of ten
events (a-c) that are formed by the combination of a set of twelve
events. These three decaplets are not independent of each other
since they have most events in common.
Figure 1: Distribution for 100 simulated 14-plets of $W$ (left panel) and $C(u, 1/E)$ (right panel). The vertical dashed lines indicate the cuts on $W$ and $C$ optimized for multiplicity and significance (Section 3).

Figure 2: Observed multiplets with 10 or more events in galactic coordinates. The size of the circle is proportional to the energy of the event. Plus signs indicate the positions of the potential sources for each multiplet. One decaplet is in fact three dependent decaplets that are formed by the combination of twelve events and the three corresponding reconstructions of the potential sources are shown.

Table 1: Deflection power, $D$; reconstructed position of the potential source in galactic coordinates, $(l, b)_S$; uncertainty in the reconstructed position of the potential source along the direction of deflection, $\Delta u_S$; and orthogonal to it, $\Delta w_S$; and linear correlation coefficient, $C$, for the largest correlated multiplets found. The data correspond to events with energy above 20 EeV from 1st January 2004 to 31st December 2010.