

Sensitivity of a search for cosmic ray sources including magnetic field effects

Martin Erdmann, Gero Müller, Martin Urban

RWTH Aachen University, Physics Institute 3A

E-mail: martin.urban@physik.rwth-aachen.de

Abstract. We analyze the sensitivity of a new method investigating correlations between ultra-high energy cosmic rays and extragalactic sources taking into account deflections in the galactic magnetic field. In comparisons of expected and simulated arrival directions of cosmic rays we evaluate the directional characteristics and magnitude of the field. We show that our method is capable of detecting an anisotropy in data sets with a low signal fraction. It also reveals directions with increased probability for sources of cosmic rays, and therefore opens new possibilities for investigating cosmic particle origin and acceleration.

1. Introduction

Ultra-high energy cosmic rays (UHECRs) are subjected to deflections in magnetic fields during their propagation from their source to Earth. Especially, the strong galactic magnetic field (GMF) leads to substantial deflections. Recent GMF models based on 40000 Faraday rotation and synchrotron emission measurements [1, 2, 3, 4, 5] can be used to predict the direction and the magnitude of these deflections.

We use the Jansson and Farrar parametrization [4] to calculate the expected arrival directions of protons for each source. This allows two types of correlation analyses to be performed, an analysis where we compare simulated arrival directions to the original source position (“uncorrected”) and a “corrected method” where we compare the arrival directions of the UHECRs to the expected arrival directions.

2. Astrophysical simulation

This analysis is based on simulations where the simulated data set is composed of signal and background events. The signal events are obtained by propagating 10^7 highly energetic nuclei from extragalactic sources to the edge of the galaxy using CRPropa3 [6]. As no sources are identified yet we select 22 active galactic nuclei (AGNs) from the Véron-Cetty-Véron catalog version 12 [7] within the GZK horizon (75 Mpc) [8] and which are close to high energy neutrinos measured by the IceCube Collaboration [9].

During their propagation cosmic rays are deflected by extragalactic magnetic fields based on large scale structure simulations [10]. Due to interactions with various backgrounds nuclei can disintegrate and thus secondary particles reach the edge of the galaxy. The galactic propagation is performed by using a lensing technique where arrival directions at the edge of the galaxy are mapped by an energy dependent matrix onto arrival directions on Earth [11]. The signal set contains $\sim 70\%$ protons and $\sim 30\%$ nuclei. For the background we simulate isotropic cosmic



rays taking into account the geometric exposure of the Pierre Auger Observatory for zenith angles below 60° [12].

As an example, Fig. 1 shows a simulated data set with $N = 231$ UHECRs consisting of 10 % signal events and 90 % events taken from the isotropic background. They are represented by gray circular symbols and have energies $E \geq 52 \text{ EeV}$. The number of events is equal to the highest energetic events published in [13]. The sources are marked by stars and their distances are color coded in red. More details on the simulation can be found in [14, 15].

3. Angular distance

Fig. 2 shows the integrated number of cosmic rays arriving within an angular distance α_0 to the original source positions (black) and the expected arrival directions (red), respectively. The excess below 5° can be explained by protons with high rigidity coming from the selected sources. Consequently we define correlating events as events within an angle α (α_{GMF}) smaller than 5° to the original (expected) arrival direction.

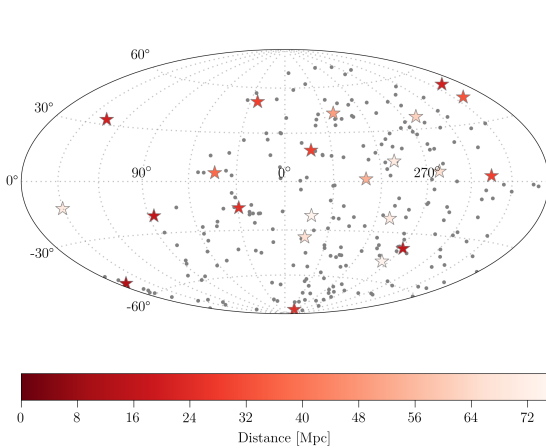


Figure 1. Simulated data set. UHECRs are shown as gray circular symbols. The distance of the AGN sources (stars) is color coded in red.

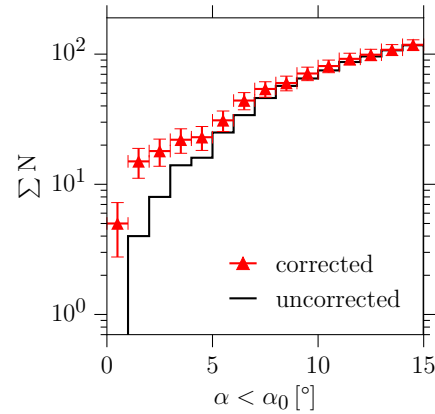


Figure 2. Total correlation frequency within angular distances α_0 : Analysis with magnetic field corrections (red symbols) and without them (black histogram)

4. Angular asymmetry

Fig. 3 shows the distribution of the difference $\alpha - \alpha_{\text{GMF}}$ for correlating events with distances below 5° . Negative entries mean that distances between cosmic rays and the corresponding source candidates have increased after the magnetic field correction whereas positive entries imply an improvement due to the field correction method. The asymmetry of the distribution is defined by eq. 1 and quantifies the change in the angular distance:

$$A = 2 \frac{N(\alpha > \alpha_{\text{GMF}}) - N(\alpha < \alpha_{\text{GMF}})}{N(\alpha > \alpha_{\text{GMF}}) + N(\alpha < \alpha_{\text{GMF}})}. \quad (1)$$

It ranges from -2 to 2 , and the value for this simulation is $A = 0.96$.

5. Clustering

For correlating events we investigate the number of sources correlating with $m = 1, 2, \dots$ cosmic rays. Fig. 4 shows the frequencies of the cluster size m for the uncorrected (black) and the corrected (red triangles) analysis. We find configurations containing singlets, doublets, triplets and a sextet. The clustering is quantified by the multinomial distribution

$$P(n_1, \dots, n_{22}; N - N_{\text{hit}}) = \frac{N!}{n_1! \dots n_{22}! (N - N_{\text{hit}})!} p_1^{n_1} \dots p_{22}^{n_{22}} (1 - p_{\text{iso}})^{N - N_{\text{hit}}} \quad (2)$$

Here n_i denotes the number of hits for source i and consequently the total number of hits is $N_{\text{hit}} = \sum_{i=1}^{22} n_i$. The remaining $N - N_{\text{hit}}$ cosmic rays have a no hit probability of $(1 - p_{\text{iso}})$ where p_{iso} is calculated by summing the hit probabilities p_i of the sources. The sum over the hit probabilities in the uncorrected analysis is $p_{\text{iso}} = 5.3\%$ taking into account the geometric exposure of the Pierre Auger observatory [12]. Due to the energy dependence of the expected arrival directions this value becomes slightly energy dependent and increases on average to $p_{\text{iso}} = 5.7\%$ for the corrected method.

To compare the analysis with and without magnetic field correction we use $\Delta \log_{10} P = \log_{10} P_{\text{GMF}} - \log_{10} P$ where large negative values mean an improvement in the clustering. We obtain $\Delta \log_{10} P = -3.8$.

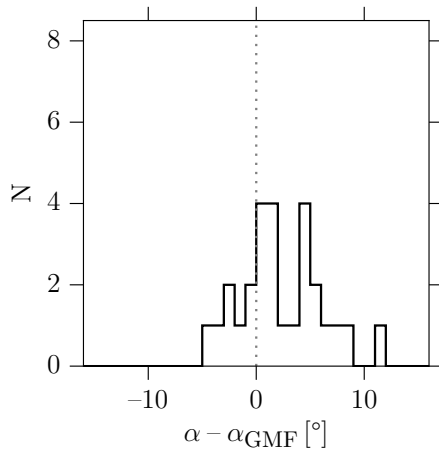


Figure 3. Difference in angular distance between correlating events within 5° for the magnetic field corrected and the uncorrected analysis method.

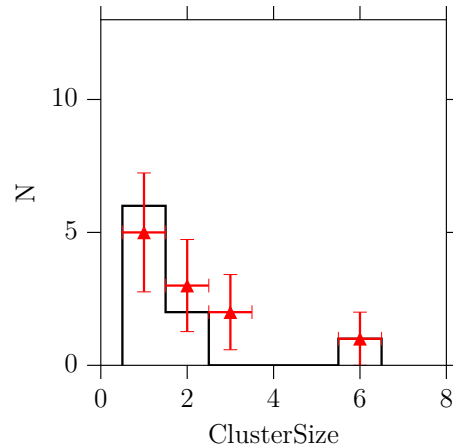


Figure 4. Frequencies of clusters for the magnetic field corrected (red triangles) and the uncorrected analysis method (black histogram).

6. Combination and sensitivity

The combination of the clustering and the angular asymmetry is shown in Fig. 5. It is compared to 10000 simulations with random field directions and isotropic cosmic rays denoted by the box symbols. This distribution is centered around 0 and only 0.47% of the isotropic events have an improvement in comparison to the values obtained in the nominal analysis. The dashed red lines help to identify the region of improvement (lower right area).

In a next step the signal fraction of the nominal simulation is varied between 1% and 50%. For each signal fraction we simulate 100 different realizations and compare them to 10000 isotropic simulations, similar to the procedure shown in Fig. 5. The significance is calculated from the

fraction of simulations with an improvement in the asymmetry A and the clustering $\Delta \log_{10} P$. We define the detection efficiency ϵ_{det} as the number of realizations for a given signal fraction where we can distinguish the simulation at the level of 3σ (5σ) from isotropy. Fig. 6 shows the dependence of the detection efficiency on the signal fraction. The solid lines denote the analysis presented in this work and the dashed lines the sensitivity using the two point auto-correlation method [16].

For signal fractions above 25 % the two point auto-correlation has an efficiency of more than 50 % to detect a deviance from isotropic arrival directions at the level of 3σ . It needs at least two cosmic rays from one source to observe a signal which is not very likely for a low number of signal events from 22 sources.

By adding directional information on source hypotheses the sensitivity can be much increased. With the method presented in this work a simulated setup with a signal fraction of 10 % can be distinguished from the isotropic distribution at the level of 5σ with a detection efficiency of 50 %. This method is fully efficient for signal fractions above 20 %.

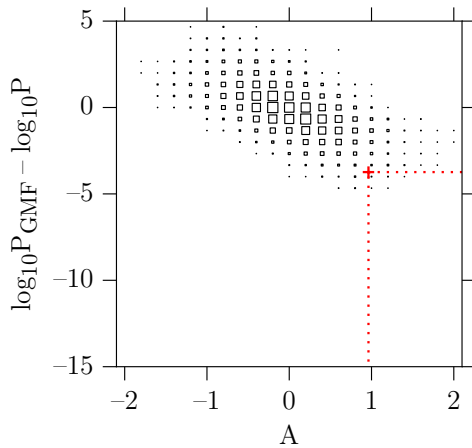


Figure 5. Combination of the asymmetry and the clustering compared to 10000 simulations with random magnetic field directions and isotropic cosmic rays.

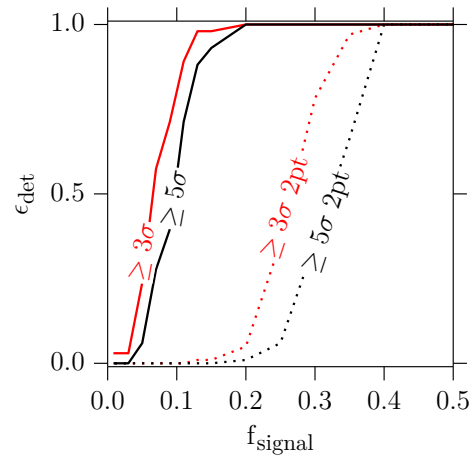


Figure 6. Detection efficiency depending on the signal fraction. The solid lines denote the method presented in this work and the dashed lines the two point auto-correlation.

7. Conclusion

In this contribution we presented the sensitivity of a method investigating correlations between UHECRs and extragalactic sources taking into account the deflections of charged cosmic rays in the galactic magnetic field.

We introduced two new variables, angular asymmetry and change in clustering. The first describes the difference in the angular distance between sources and cosmic rays before and after a magnetic field correction. The clustering observable counts the number of correlating cosmic rays per source for uncorrected and corrected arrival directions.

We have shown that the combination of both variables is sensitive to detect a deviation from isotropic arrival directions in simulated events with a signal fraction at the level of a few percent.

In general, this method of magnetic field corrections allows to study both, the galactic magnetic field and source directions provided e.g. by a source catalog or uncharged cosmic particles.

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