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Methods for searching UHECR anisotropies with the Pierre Auger Observatory

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The Pierre Auger Observatory, currently under construction, is a detector of Ultra-High Energy Cosmic Rays (UHECR), which will allow to study the highest-energy particles with unprecedented statistics. The aim of this paper is to present methods which are currently under development within the Auger Collaboration to study possible anisotropies of UHECR which are a major key to understand their origin.

1 Introduction

A key to solve the pending mystery of UHECR is the possible observation of unambiguous sources in the sky, which would allow to understand the origin of these particles. The Pierre Auger Observatory [1] will be able to study these anisotropies with a much higher statistics than previous experiments. Systematics will be controlled thanks to a hybrid mode incorporating both a ground-based array of water Cerenkov tanks (the Surface Detector) and fluorescence telescopes placed on the boundaries of the surface array. A review on the Auger Observatory status and performances can be found in [2].

Here we first present two technical tools of prime importance to study UHECR anisotropies, namely: the arrival direction reconstruction of Auger Surface Detector events, and the sky exposure estimations. We then focus on some methods to study large-scale patterns as well as localized sources.

2 Angular reconstruction and resolution with the Surface Detector

The Surface Detector consists of 1600 tanks on a triangular grid of 1.5 km spacing. The direction of the primary particle that generates a shower can be inferred from the direction of the shower axis, which can be reconstructed from the arrival time of the shower front in the individual tanks. The reconstruction is done in three steps. In the first one, the shower front is assumed to be a plane propagating with the speed of light. The actual curvature of the front is then taken into account, and in the third step, the position of the shower core is fitted from signal intensity in the tanks. The second and third steps can only be applied for events with four or more tanks, but yield a better pointing accuracy.

The angular resolution of the detector depends mostly on the shape of the array, as well as on the size of the tanks. As the particle density decreases rapidly with the distance from the core, we have a Poisson limited sampling of the shower ground density, which actually dominates the timing fluctuations.

Furthermore, the thickness of the shower front increases as the distance to the core increases. As a consequence, the accuracy with which the shower front arrival time can be determined decreases with distance to the core; this is taken into account when estimating the arrival direction of a shower.

Simulations have been undertaken to estimate as well as to optimize the angular resolution of the Surface Detector. The expected resolution at $E \sim 10^{19}$ eV is around one to two degrees, but it should be noted that the resolution varies a lot depending on the zenith angle θ as well as on the energy E of the shower: the higher θ or E, the more tanks are hit, and therefore the better the resolution is.

Since the Auger Observatory uses a hybrid technique with both surface and fluorescence detectors, studies are under way to take advantage of this in order to estimate the angular resolution independently of the simulations. Thanks to both informations from the tanks and the fluorescence telescopes, the arrival direction of "hybrid" events can be determined with a better accuracy than for events reconstructed with the Surface Detector alone. Comparing the "Surface Detector" and the "hybrid" arrival directions of hybrid events allows therefore to estimate the angular resolution for the Surface Detector.

3 Exposure estimation

In order to search for anisotropies one needs an estimate of the isotropic expectation of the number of events from any given direction. Two complementary methods are used to compute this exposure.

3.1 Computation from acceptance

The array acceptance is computed for any given time, using monitoring data such as the trigger activity of each tank. In order to calculate the acceptance one also needs to compute the zenith angle distribution of the events. This can be done by using an analytical formula (in the case of a perfect, saturated acceptance), by using simulations, or more simply an empirical fit on the data as is done for Fig. 1.

It is then possible to derive the exposure in any direction of the sky, by integrating the acceptance over the array working period. This allows in particular to take into account the growth of the array and possible times when individual tanks are down. The resulting exposure map is shown on the left panel of Fig. 1.

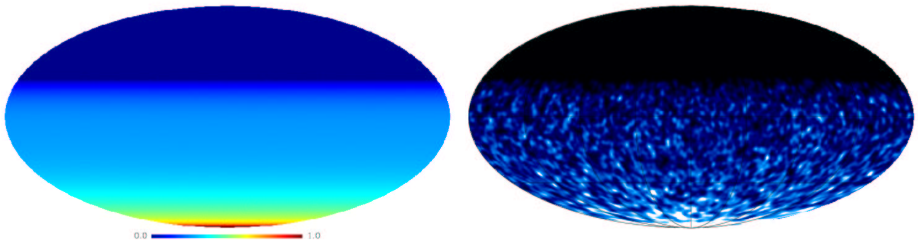

Figure 1: Left: Example of exposure map in equatorial coordinates computed from the acceptance for a very preliminary data set, which consists of events from the year 2004 which pass a so-called T5 quality trigger and which are reconstructed with at least 4 tanks. Right: The corresponding preliminary event map, smoothed with a 3-degree gaussian beam.

Particular care with respect to possible systematics must be taken when computing the exposure with this method. Many systematic effects can appear especially at low energies, when the acceptance is not saturated. As an example, weather conditions can affect the event rate: the ground density of showers is slightly changed when atmospheric conditions vary, and besides the detector electronics and calibration may also vary as a function of weather. If such systematics appear to be important, one can use pressure and temperature informations to apply a correction to the exposure map.

3.2 Scrambling method

This method consists of building a large number of randomized event sets from a given true event set. The randomized events are built such that the distributions of zenith angle, azimuth and time remain unchanged. A large number of randomized event maps are then created. The derived exposure is the mean of all these maps.

Compared to the previous method, the scrambling (or "shuffling") has the important advantage of incorporating the above-mentioned systematic effects. However, such a method can also hide real large-scale anisotropy patterns. Furthermore, due to the fact that the exposure is derived directly from a finite event set, the accuracy is lower than for the first method.

4 Large-scale feature analysis

The study of possible large-scale features on Auger data is motivated by various reasons: because of deflections by galactic and extragalactic magnetic fields, it is expected that rather large-scale patterns appear, at "low" energies ($E \sim 1$ EeV) but also perhaps at the highest energies [3]. The AGASA Collaboration has observed a large-scale excess of events, correlated with the Galactic Center, at energies ~ 1 EeV [4]. Correlations with extended objects, such as the Galactic or Supergalactic Planes, might also appear. Searches for large scale features are particularly sensitive to systematic effects because they produce similar patterns.

One commonly used method within the cosmic ray community to detect large-scale patterns is to apply the so-called Rayleigh analysis. From a set of n event right ascensions α_i, one computes the amplitude:

$$A = \sqrt{a^2 + b^2} \quad \text{with} \quad a = \frac{2}{n} \sum \cos \alpha_i \ \text{ and } \ b = \frac{2}{n} \sum \sin \alpha_i$$

We can then estimate the probability to have a Rayleigh amplitude A larger or equal than the measured one, assuming a uniform distribution of right ascensions. A small probability is a signature for anisotropic patterns. However, this method is limited as it does not use the information contained in the declinations of the events, and does not use explicitely the sky exposure. More sophisticated methods have been developed. We give here two examples:

- Reconstructing a possible dipole amplitude as well as its orientation from the data [5,6]. This method requires the knowledge of the exposure, and it works in the case of partial sky coverage, as is the case for Auger South. It consists in fitting the dipole parameters using a set of analytical equations one can obtain assuming that the large-scale anisotropies we might observe consist in a perfect dipole.

- Angular power spectrum estimation [7]. This method consists in expanding the fluctuations $\Delta(\mathbf{n})$ of the event number on the spherical harmonics basis according to:

  $$\Delta(\mathbf{n}) = \sum_{\ell \geq 0} \sum_{m=-\ell}^{m=\ell} a_{\ell m} Y_{\ell m}(\mathbf{n})$$

  It has been shown [8] that the Auger South exposure is large enough so that one can measure the angular power spectrum from the data, assuming a stochastic and statistically homogeneous field.

5 Small-scale feature analysis

There are obvious reasons to look for small scale features. At the highest energies, the increase of the Larmor radius of charged particles in astrophysical magnetic fields as well as the reduction of the horizon due to GZK-like interactions might favor the emergence of point-like UHECR sources. Furthermore, at EeV energies, we might see neutrons coming from the Galactic Center (GC), as has been proposed to explain both the AGASA excess and the more recent HESS GC TeV source[9].

Statistical analysis, such as the autocorrelation function, nearest neighbour distribution[10], etc, are under way with the first Auger data. Direct source searches are performed using a "prescription"[11] to avoid the sometimes ambiguous estimate of penalties. Indeed, in particular at the highest energies, the low statistics is such that it is always possible to find some "pattern" from the data if a large number of trials are made. Therefore, before data taking, a probability of 10^{-3} was fixed and assigned to a few a priori sources, like the GC. Naturally, other blind source searches, without any *a priori* target, are also carried out on the data.

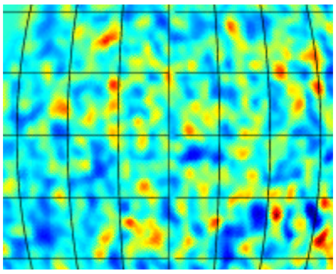

Figure 2: An example of smoothed event map, centered on the Galactic Center. The preliminary event set is the same as in Fig. 1 (there is no energy cut). The grid size is 15 degrees. The exposure has been subtracted.

6 Conclusion

The first Auger event maps are now being analysed. The angular resolution of the Surface Detector depends on the energy and zenith angle of the showers. Its expected order of magnitude above 10^{19} eV is around one degree. We use complementary methods to estimate the background, which are particularly useful to understand some subtle behaviors of the detector. Original methods have been developed to study possible anisotropies on the large scales (dipole reconstruction, angular power spectrum) as well as on the small scales (clustering signals). As the statistics is increasing rapidly, the first physics results should come soon.

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