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Search methods for UHECR anisotropies within the Pierre Auger Observatory

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The Pierre Auger Observatory is a hybrid detector of UHECR, currently under construction, which will allow to study these highest-energy particles with unprecedented statistics and control of systematics [1]. The aim of this talk is to present methods which are currently under development within the Auger Collaboration to study UHECR anisotropies, which are a major key to understand their origin. We also give a very preliminary insight on what the "Auger sky" looks like.

1 Angular reconstruction and resolution with the Surface Detector

The reconstruction of arrival directions for particles detected by the Auger Surface Detector is part of the full event reconstruction pipe which is needed to recover the major features of the showers. To measure the arrival direction of a shower, one needs to use mostly the arrival times of particles from the shower in the different water tanks constituting the Surface Detector, and to perform an iterative fit from the data. A first estimation of an event arrival direction is carried out by assuming that the shower front is plane. This estimate is the one we keep in the case of a 3-tank only shower, ie. for low-energy events.

If at least 4 tanks are hit by the shower, more time differences between the tanks are available and allow us to take into account the radius of curvature of the shower. To do so, one needs to estimate the shower core location, which is done accurately by performing a Lateral Distribution Function fit on the tank signals.

The angular resolution depends largely on the accuracy with which the shower arrival times are measured in the tanks. Two major factors have an influence on this accuracy:

1. The PMT signals in the tanks are recorded with 40 MHz FADC, which implies a 25 ns binning of the signals.

2. The width of the shower front increases when the distance to the core increases. As a consequence, the accuracy on the shower front arrival time decreases with distance to the core.

Simulations have been undertaken to estimate as well as optimize the angular resolution of the Surface Detector. The expected resolution at ultra-high energies is around 1 degree, 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.

To conclude, a simulation independent estimation of the angular resolution will be performed, taking advantage of the hybrid detection mode of Auger.

2 Exposure estimation

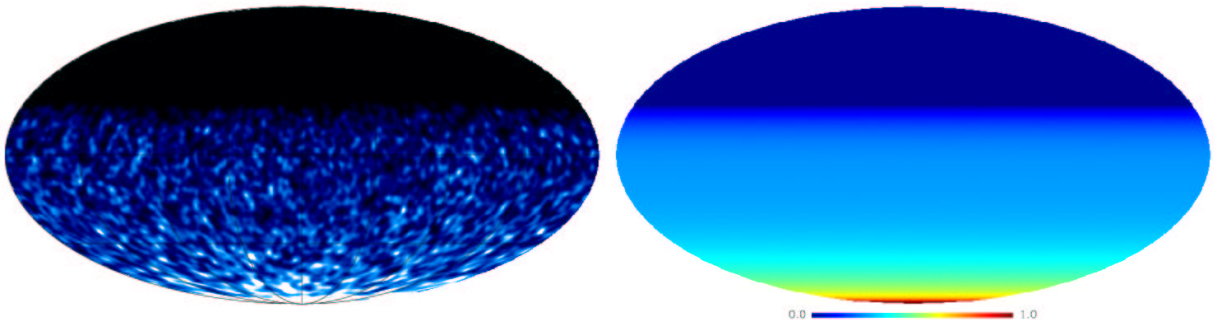

Figure 1: Left: An example of Auger event map, smoothed with a 3-degree gaussian beam. The data set is preliminary, and consists of events from the year 2004 which pass a so-called T5 quality trigger and which are reconstructed with at least 4 tanks. Right: Corresponding exposure map computed from the acceptance.

The background estimation is of considerable importance to study possible anisotropies with Auger. Two complementary methods are used to compute the coverage.

2.1 Computation from acceptance

The array acceptance is computed at any time, using the monitoring data which are sent by the tanks. One can then 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 and possible dead-times of the detector. The resulting exposure map is shown in Fig. 1.

To do so, one needs naturally to compute the zenith angle distribution of the events. This can be done using an analytical formula (in the case of a perfect, saturated acceptance), or using simulations, or more simply an empirical fit on the data.

A particular care on 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 physics of showers is slightly changed when atmospheric conditions vary, and the detector electronics and calibration can also vary. In this case, one can use the monitoring of pressure and temperature which is carried out at each Fluorescence Detector site to apply a correction to the exposure map.

2.2 Scrambling method

This method consists in building a large number of Monte-Carlo event sets from a given true event set. The Monte-Carlo events are built to keep the same distributions in zenith angle, azimuth and solar time as for the true events. One therefore disposes of a large number of simulated event maps. The exposure is then simply taken as the mean of all these maps.

Compared to the previous method, the scrambling (or "shuffling") has the important advantage of removing the relevant systematic effects, even if they are not controlled. However, such a method can also remove real large-scale anisotropy patterns. Furthermore, due to the fact that the exposure is derived directly from a finite event set, small fluctuations remain on the shuffled sky maps.

3 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, one might expect rather large-scale patterns to appear, at "low" energies ($E \sim 1$ EeV) but also perhaps at the highest energies [2]. The Agasa collaboration has already claimed for a large-scale excess of events, correlated with the galactic center, at energies ~ 1 EeV [3]. To perform large-scale feature searches, one must be particularly careful because of possible systematics in the exposure, as explained previously.

The standard method used within the CR community to detect large-scale patterns is to apply the so-called Rayleigh analysis. From a set of event right ascensions α_i, one computes the amplitude:

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

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 within the Collaboration:

- Reconstructing a possible dipole amplitude as well as its orientation from the data. 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.
- Angular power spectrum estimation [4,5]. This method is inspired from CMB analysis: the fluctuations $\Delta(\mathbf{n})$ of the event number are expanded on the spherical harmonic basis according to:

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

  Assuming a stochastic and spectrally homogeneous field (otherwise it does not make a lot of sense to compute an angular power spectrum), the estimator is then given by:

$$\tilde{C}_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=\ell} |a_{\ell m}|^2$$

  Things are complicated by the partial sky coverage: indeed, due to non-uniform exposure, the estimated power spectrum is related to the true one by the relation:

$$\langle \tilde{C}_\ell \rangle = \sum_{\ell'=0}^{+\infty} M_{\ell\ell'} C_{\ell'}$$

  The mode-mixing matrix $M_{\ell\ell'}$ can be computed from the exposure. It appears that Auger South exposure is large enough so that one can invert correctly this matrix, and therefore measure the true angular power spectrum from the data.

4 Small-scale feature analysis

There are obvious reasons to look for small scale features. At the highest energies, the increase of charged particle Larmor radius 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, as has been proposed to explain both the Agasa excess and the more recent HESS GC TeV source [6].

Statistical analysis, such as the autocorrelation function, nearest neighbour distribution [7], etc, are under way with the first Auger data. Direct source searches are performed using a "prescription" rule [8] which has been adopted by the Collaboration in order to prevent itself from wrong claims. Indeed, in particular at the highest energies, the low statistics is such that we will always be able to find some "pattern" from the data if a large number of trials are made. Therefore, before data taking, it was decided to fix a probability of 10^{-3} and to distribute it over a few a priori sources, determined in advance. For the 2004 data, most of this probability has been attributed to the Galactic Center.

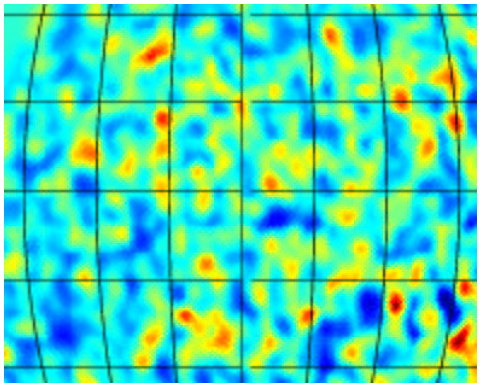

Figure 2: An example of smoothed event map, centered on the Galactic Center. The preliminary event set consists of events from 2004, satisfying a T5 quality trigger and reconstructed with more than 4 tanks. The grid size is 15 degrees. The exposure has been substracted. No obvious excess appears from the Galactic Center with this set.

Naturally, other blind source searches are also carried out on the data, in order to feed possible new prescriptions.

5 Conclusion

The analysis of the first Auger event maps is going on. The angular resolution of the Surface Detector depends on the energy and zenith angle of the showers, but its expected order of magnitude is 1 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 (source prescriptions). As the statistics is increasing rapidly, the first physics results should come soon.

References

1. The Pierre Auger Project Design Report, Fermilab (1995)
2. Sigl, G. et al., PRD 70 (2004) 043007
3. Hayashida, N. et al., Astropart. Phys. 10 (1999) 303
4. Sommers, P., Astropart. Phys. 14 (2001) 271
5. Deligny, O. et al., JCAP 0410 (2004) 008
6. Aharonian, F. et al., `astro-ph/0408145`
7. Harari, D. et al., JCAP 0405 (2004) 010
8. Clay, R., Proc. 28th ICRC (2003), Tsukuba