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Searches for cosmic ray anisotropies at ultra-high energies

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We report the different analyses of the arrival directions of ultra-high energy cosmic rays detected at the Pierre Auger Observatory. In the range of energy considered there, two kinds of anisotropies are expected to be observed : point sources at the highest energies and large-scale pattern at lower energies. We report the update of the correlation with Active Galactic Nuclei. Then, from the apparent excess in the particular direction of Centaurus A above 55 EeV, we derive constraints on the proton fraction at lower energies. Finally, we report on the detection of a possible large-scale pattern.

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1. Introduction

The study of anisotropies is a crucial tool for the global understanding of cosmic rays. At the highest energies, above $4-5\times10^{19}$eV, if ultra-high energy cosmic rays (UHECR) have an extragalactic origin, a flux suppression is expected to occur due to their interaction with the cosmic microwave background and infrared photons. This is the so-called GZK effect [1], suggesting a relative proximity of the sources. In this case, the rigidity of the UHECRs allows us to expect fundamental information on their origin by the detection of point sources.

Since 2005, the Pierre Auger Collaboration has been reporting on anisotropy studies [2, 3]. In 2007, evidence for anisotropy in the arrival directions of UHECR [4] at 99% c.l. was shown by measuring the fraction of events correlating with the Véron-Cetty and Véron catalog sources (VCV). The parameters of this correlation were an energy threshold of 55 EeV, an angular separation between the events and the AGN smaller than 3.1°, and a maximum distance of the AGN of 75 Mpc. An update of this correlation is presented in Sec. 2.1. As it was already pointed out in [4], two out of the 27 highest energy events observed before August 2007 by the Pierre Auger Observatory arrived within less than 3° of Centaurus A, with several more events lying in the vicinity of its radio lobes. In Sec. 2.2, we assume different chemical compositions at the source, deriving limits on the proton fraction from the observations of the level of anisotropies at lower energies.

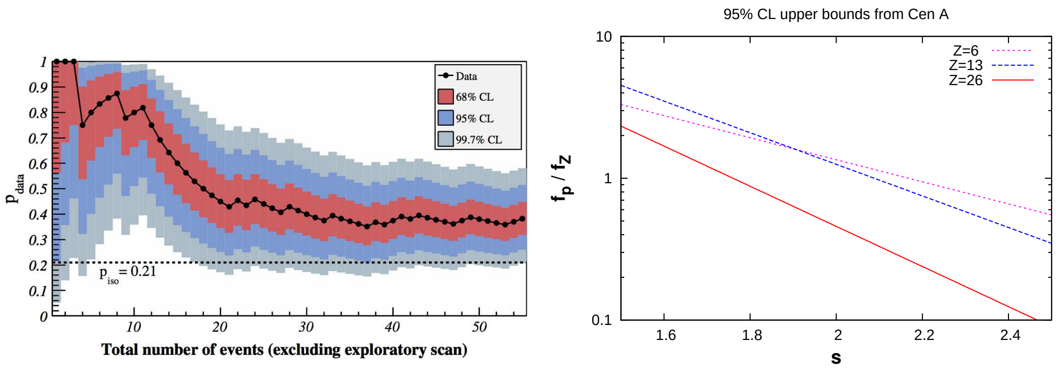
Furthermore, at lower energies, around 1 EeV (1 EeV $=10^{18}$ eV), we can expect to detect dipolar large-scale patterns. A possible scenario is that the sources are galactic up to the ankle ($\sim$ 4 EeV), this hardening of the energy spectrum marking the transition from galactic to extra-galactic sources. A dipolar large-scale pattern with an amplitude at the percent level is expected to occur as a signature of cosmic rays escaping the Galaxy [5]. Even for isotropic extragalactic cosmic rays, a dipole anisotropy may exist due to our motion with respect to the frame of extragalactic isotropy through the *Compton-Getting effect*. We report on both phase and amplitude measurements of the first harmonic modulation in the right-ascension (RA) distribution and the deduced upper limits on the amplitudes in Sec. 3.

The Pierre Auger Observatory [6] is the largest cosmic ray observatory with its 1600 water Cherenkov detectors place on a triangular grid with a 1.5 km spacing, covering an area of 3000 km^2. It is in operation since 1 January 2004 and construction was completed in June 2008. In addition to the surface detector (SD) array, a fluorescence detector (FD) allows a calorimetric measurement of the energy deposit in the atmosphere. The trigger requirement for the SD is based on a 3-fold coincidence. A fiducial cut is applied ensuring full efficiency for CR primary energies $E>3$ EeV. The arrival directions are obtained through the differences in the time of flight of the shower front leading to an angular resolution from $\sim2^\circ$ down to 0.9° at the highest energies [7]. The statistical uncertainty from shower-to-shower fluctuations and the calibration curve obtained by combining the FD and the SD energy estimation amounts to about 15%. The absolute energy scale is given by the fluorescence measurements and has a systematic uncertainty of 22% [8].

2. Anisotropies at the highest energies

2.1 Update of the Véron-Cetty and Véron catalog correlation

At the end of December 2009, the current estimate of the amount of correlation is (38^{+7}_{-6})%,



(a) (b)

Figure 1: *Left panel*: Evolution of the correlating fraction of events up to the end of December 2009. *Right panel*: Upper bounds at 95% CL on the allowed proton to heavy fractions in the source as a function of the assumed low energy spectral index *s*.

with 21 correlating events out of 55 while the fraction expected under the isotropic hypothesis is 21%. The evolution of the correlating fraction of events is shown in Fig. 1(a).

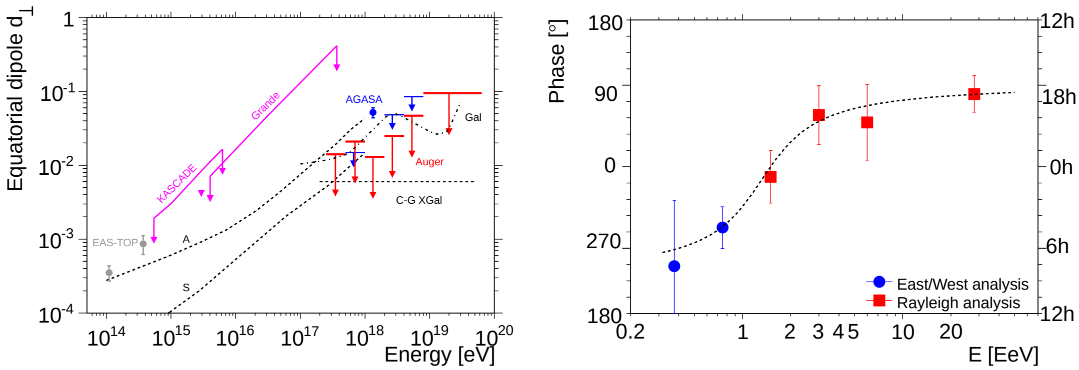
Note that these locations of AGNs in the VCV catalog may well be acting just as tracers of the actual UHECR sources. In the same paper where the update is reported [9], alternative studies with other populations also indicate some degree of correlation within a few degrees with those objects. The identification of the UHECR sources will require much larger statistics.

2.2 Constraints on the proton fraction

Following an idea proposed in [10], which exploits the fact that a high energy anisotropy due to nuclei of charge Z should lead to an anisotropy in the same region of the sky at energies Z times smaller due to the protons from the same sources, we are able to constrain the allowed proton fraction at the source under different assumptions on the value of the nuclear charges responsible for the high energy excess. In [11], we took into account the uncertainty on the excess in the direction of Centaurus A, and derived upper bounds on the proton fraction which are shown on 1(b) for different values of both Z and spectral index at the source. A similar study for the events correlating with the VCV catalog was done.

3. Large scale anisotropies

The statistics accumulated in the 1 EeV energy range by the SD allows one to be sensitive to intrinsic anisotropies with amplitudes down to the 1% level. This requires determination of the exposure of the sky with a corresponding accuracy as well as control of the systematic uncertainty of the variations in the counting rate of events induced by changes of atmospheric conditions and the variation of the size of the array. After carefully correcting these experimental effects, we present searches for first harmonic modulations in RA based on the classical Rayleigh analysis. Below $E \sim 1$ EeV, the detection efficiency of the array depends on zenith angle and composition. Consequently, our results below 1 EeV are derived using event counting rate differences between Eastward and Westward directions [12] that allow a search for anisotropy in RA without requiring



(a) (b)

Figure 2: *Left panel*: Upper limits on the anisotropy amplitude of first harmonic in RA as a function of energy from this analysis. *Right panel*: Phase of the first harmonic as a function of energy. More details on the legendare given in Ref. [14].

any evaluation of the detection efficiency. The results on the amplitudes do not provide any further evidence in favor of a significant anisotropy, but upper limits on modulations in RA of UHECRs can be derived (Fig. 2(a)). It has been pointed out [13] that a consistency of the phase measurement in ordered energy intervals is expected already at lower statistics than that required for the amplitude to significantly stand out of the background noise if there is a weak anisotropy signal. The phase measurement is reported in Fig.2(b), showing a smooth transition from $\sim 270^\circ$, the Galactic Center direction, up to $\sim 90^\circ$, the Galactic anti-Center direction. For more details on this analysis, see [14].

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