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Anisotropy studies with the Pierre Auger Observatory

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Abstract. Recent results from the Pierre Auger Observatory about anisotropies in the arrival directions of ultra-high energy cosmic rays are reported. In the EeV energy range, we present the results of a search for a large scale dipolar anisotropy pattern. In the same energy range, we show the results of a search for localized excesses of cosmic ray neutrons. For cosmic rays with energies above 20 EeV, we discuss the results of the search for multiplets of aligned events. Finally, we present an update on the search for correlations between events with energy above 55 EeV and the positions of active galactic nuclei from the Véron-Cetty and Véron catalog. The results of a study of the region around Centaurus A are also shown.

1. INTRODUCTION

In this article, we summarize recent results of the Pierre Auger Observatory on anisotropy searches. Anisotropies in the distribution of ultra-high energy cosmic rays (UHECR) are a key observable towards understanding their origin and identifying the transition region from galactic to extragalactic cosmic rays. In the energy range where galactic sources dominate the flux, models predict both a dipolar and a quadrupolar anisotropy, determined by the galactic magnetic fields and the source distribution of cosmic rays in the galaxy. If such an anisotropy can be detected, the transition to extragalactic cosmic rays should reveal itself by a change in the anisotropy pattern towards isotropy. Results on large-scale anisotropies are presented in section 2. Galactic neutrons in the EeV range live long enough to reach the Earth from the galactic center before decaying. If such neutrons are present they would point to their sources in the galactic disk. A search for neutron point sources is presented in section 3.

At energies of tens of EeV, where cosmic rays are suspected to be of extragalactic origin, cosmic rays may be only weakly deflected by the extragalactic magnetic fields. This opens the possibility of identifying the extragalactic sources of UHECR from their arrival directions. In section 4 we present the 2011 update on the correlation of the highest energy events with the Véron-Cetty and Véron catalog of Active Galactic Nuclei (AGN). Centaurus A is a particularly promising candidate for being an UHECR source and is discussed separately. Finally, in section 5, we review an analysis searching for multiplets of particles from a common source, deflected in a coherent galactic or extragalactic magnetic field.

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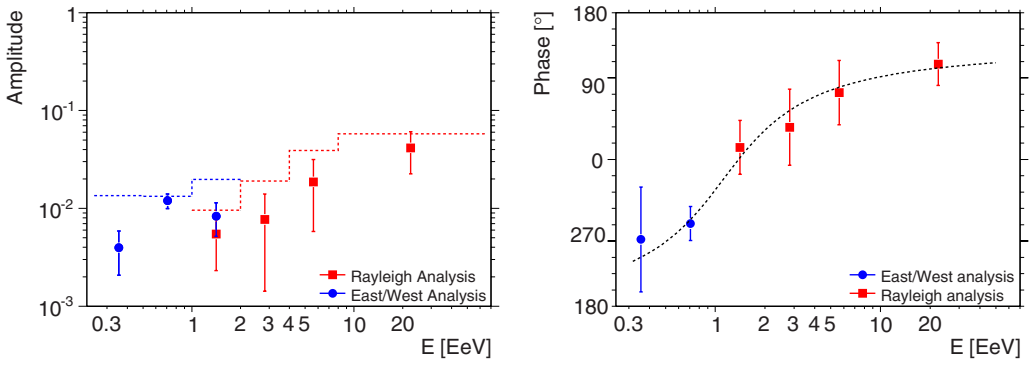

Figure 1. *Left*: amplitude r of the first harmonic as a function of energy [3]. Dashed line: 99% C.L. upper bound for isotropic fluctuations. *Right*: phase ϕ of the first harmonic as a function of energy [3]. The dashed line illustrates a smooth transition.

2. LARGE-SCALE ANISOTROPY SEARCH

Large-scale anisotropy searches use a Fourier or spherical harmonics analysis to extract possible large-scale patterns in the angular distribution of UHECR. The current statistics allow to detect a dipolar component with sensitivity at the $\simeq 1\%$ level. Predictions for the dipolar amplitude for galactic sources were obtained in diffusion models (see for example [1]) and by Monte Carlo simulation of particle trajectories (see for example [2]), but are poorly constrained due to the uncertainty on the galactic magnetic field. The expected amplitude depends strongly on the charge of the primary particles.

2.1 Method and systematics

Two different methods were used by the Auger collaboration to perform a 1-dimensional large-scale anisotropy search, the Rayleigh method [4] and the East-West method [5]. In the classical Rayleigh analysis a Fourier Transformation is performed to extract the first harmonic amplitude in the right ascension distribution α_i of the events. Systematic effects that have been studied and corrected for include the influence of the atmospheric conditions on the energy estimation and the non uniform exposure in time. At low energy, $E < 1$ EeV, the Auger data set offers large statistics, but systematic effects are stronger and more difficult to control. At these energies it is therefore preferable to use the East-West method, which is largely independent of such effects. This method makes use of the difference in the event counting rate measured in the East sector, $I_E(\alpha^0)$, and the West sector, $I_W(\alpha^0)$, as a function of local sidereal time α^0, both of which are equally influenced by detector instabilities and atmospheric effects. An anisotropy search, taking into account the full spherical distribution of the events, will be published soon.

2.2 Results for first harmonic modulation in RA

The first harmonic analysis described above was applied to the data collected by the surface detector array between 1st January 2004 and 31st December 2010 in [3]. The analysis was performed using energy intervals chosen in a logarithmic spacing $\Delta \log_{10}(E) = 0.3$ below 8 EeV. All events above 8 EeV are gathered in a single energy interval. Figure 1 shows the amplitude r as a function of energy together with the 99% C.L. upper bound on the amplitude that could result from fluctuations in an isotropic distribution. The amplitudes over the whole energy range are consistent with isotropy.

Figure 1 shows the phases for the same energy intervals. While the amplitudes gave no evidence for an anisotropy, the phases show an interesting correlation, that is unlikely to arise from an isotropic

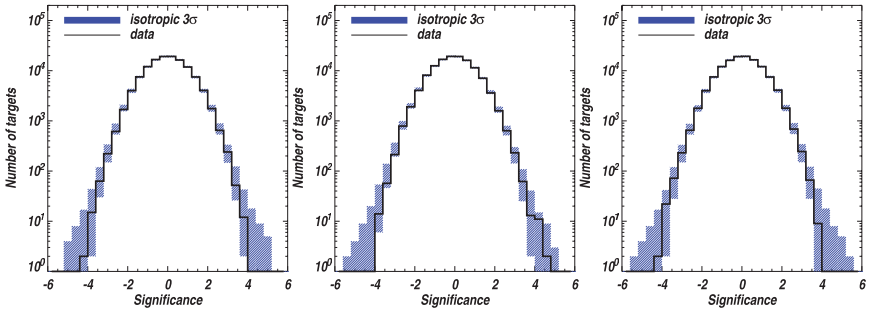

Figure 2. Distribution of the Li-Ma significances of the blind searches for neutron point sources, together with the 3σ containment of 5000 Monte-Carlo samples of an isotropic sky [6]. From left to right: [1–2] EeV, [2–3] EeV, and $E \geq 1$ EeV.

background distribution. The data suggests a smooth transition between a common phase about $\alpha \simeq 270^\circ$, in the first two bins, and another phase $\alpha \simeq 100^\circ$ for higher energies. The low energy phase is compatible with the right ascencion of the galactic center $\alpha_{GC} \simeq 268.4^\circ$, which is interesting since experimental data and theoretical models suggest that there might be a transition from galactic to extragalactic origin at an energy of a few EeV. The above being an a posteriori analysis, it is not possible to give a confidence level on the observed smooth transition. It is worth noting that the phase analysis can be shown to be more sensitive to anisotropy than the detection of amplitudes. It will be interesting to compare the observed behaviour of the phase to the measurements in future independent data.

3. SEARCH FOR EEV NEUTRONS POINT SOURCES

The mean decay length of neutrons in the EeV energy range is approximately $\lambda_n = 9.2 \times (E/1\,\mathrm{EeV})$ kpc. The detection of EeV neutrons from sources in the galactic disk is thus in principle possible. Such high energy neutrons can be produced by interaction of accelerated protons with the matter and radiation surrounding the accelerator. Neutrons have the observational advantage that they are not deflected by galactic magnetic fields. Galactic neutron sources could thus produce point-like excesses in the angular distribution of cosmic rays. An analogous argument can be made for gamma rays, but these acquire a smaller fraction of the energy of their parent particle and are thus expected to have a much lower flux.

The search for galactic flux excesses was performed in both a blind search and a targeted search in [6]. The data used in this analysis was collected between January 1st 2004 and December 31st 2010 and split in three energy intervals of $[1-2]$ EeV, $[2-3]$ EeV, and $E \geq 1$ EeV.

3.1 Blind search

To perform a blind search on the visible part of the sky, this one is divided into overlapping target regions, defined by a top-hat centered around the targets. The size of the top hat is optimized to achieve a maximum signal to noise ratio depending on the angular resolution ψ of the Surface Detector. The ideal size is 1.05ψ, where ψ is around $1^\circ - 2^\circ$, the exact value depending on the energy. The analysis uses a HEALpix grid with resolution parameter $N_{side} = 128$ defining the center points of the target regions. In each region, the number of arrival directions is counted and the Li-Ma significance in the target is evaluated. Figure 2 shows the distribution of significances, together with the bands obtained from 5000 isotropic Monte Carlo simulations, calculated for the same coverage. No significant excess is observed. Figure 3 shows a sky map with flux upper limits for the energy range $E \geq 1$ EeV.

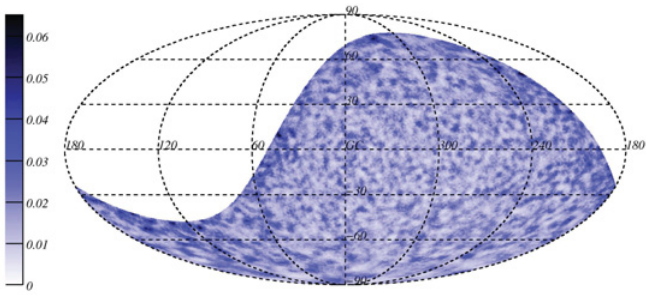

Figure 3. Flux upper limits celestial maps (in unit of $km^{-2}\ yr^{-1}$) in Galactic coordinates for $E \geq 1$ EeV [6].

3.2 Targeted search

For the targeted search, a number of bright gamma ray sources were selected. This is motivated by the fact that a number of theoretical UHECR accelerator candidates are expected to be strong gamma ray emitters in the GeV and TeV range. Targets were selected from Fermi LAT [7] (100 MeV – 100 GeV) and HESS [8] (100 GeV – 100 TeV), fulfilling a number of selection criteria. The ten brightest γ ray sources from both catalogs fulfilling these criteria were analysed for a possible flux excess and no such excess was found.

4. CORRELATION OF THE HIGHEST ENERGY COSMIC RAYS WITH NEARBY AGNS

The Auger collaboration has studied the correlation of the highest energy events above the Greisen-Zatsepin-Kuz'min (GZK) energy threshold at 6×10^{19} eV with several catalogs of astrophysical objects. We present here the correlation with the Véron-Cetty and Véron catalog (VCV), that was first published in [9] and then updated in [10] and [11]. We also present the search for an excess from the Centaurus A region.

4.1 Update of the VCV correlation signal up to June 2011

To establish a confidence level for the rejection of the isotropic hypothesis, the initial analysis [9] used part of the available data as exploratory data to optimize the analysis parameters. The parameters obtained were energy $E \geq 55$ EeV, maximum redshift $z_{\rm max} = 0.018$ ($d_{\rm max} \simeq 75$ Mpc) and maximum angular separation $\psi = 3.1^\circ$. The rest of the available data was used to establish the confidence level. This analysis was recently updated in [11], keeping the parameters of the initial analysis. Up to June 2011 (excluding exploratory data), 28 out of 84 events correlated within the chosen parameters. The degree of correlation $p_{\rm data} = k/N$ as a function of the total number N of time-ordered events is shown in Figure 4. The current value is $p_{\rm data} = 33 \pm 5$ % compared to 21% expected from isotropy.

4.2 Excess in the Cen A region above 55 EeV

An excess of events above 55 EeV around the direction towards Centaurus A, a close AGN ($d = 3.8$ Mpc) was observed initially in [9]. The largest excess from isotropy with additional data was found for an angular window of size $\psi = 18^\circ$ [10]. In [12] that same region was examined also at lower energies. This angular window includes 10 out of 60 events above 55 EeV in the data set of this analysis, while 2.44 are expected from isotropy. At lower energies no excess was found. This leads to constraints on the source proton fraction if high energy anisotropies are due to heavy nuclei of charge Z [13]. The

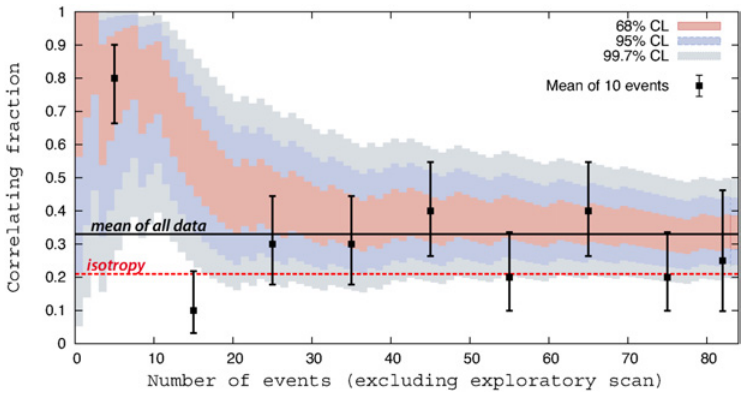

Figure 4. The most likely value of the degree of correlation $p_{\rm data} = k/N$ is plotted as a function of the total number of time-ordered events (excluding those in period I) [11]. The 68%, 95% and 99.7% confidence level intervals around the most likely value are shaded. The horizontal dashed line shows the isotropic value $p_{\rm iso} = 0.21$ and the full line the current estimate of the signal $p_{\rm data} = 0.33 \pm 0.05$. The black symbols show the correlation fraction in independent bins with 10 consecutive events.

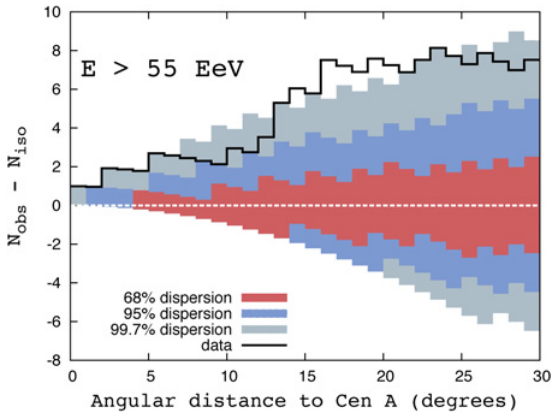

Figure 5. Cumulative number of events with $E > 55$ EeV (subtracting the average isotropic expectations) as a function of angular distance from the direction of Cen A [12]. The bands correspond to the dispersion expected for an isotropic flux.

cumulative number of events as a function of angular distance from the direction of Cen A is shown in Figure 5.

5. SEARCH FOR MULTIPLETS OF ALIGNED EVENTS

A search for groups of directionally-aligned events ('multiplets') which exhibit a correlation between arrival direction and the inverse of the energy was presented in [14]. Such an alignment is expected from sets of events coming from the same source after having been deflected by intervening coherent magnetic fields. An observation of such multiplets would allow to extract information about the strength and distribution of coherent galactic or extragalactic fields. From the data set of 1509 events above 20 EeV collected between 1st January 2004 and 31st December 2010, multiplets with high correlation between deflection angle and energy were extracted. The largest multiplets that were found are one 12-plet and 2 independent 10-plets, shown in Figure 6. The chance probability to obtain from an

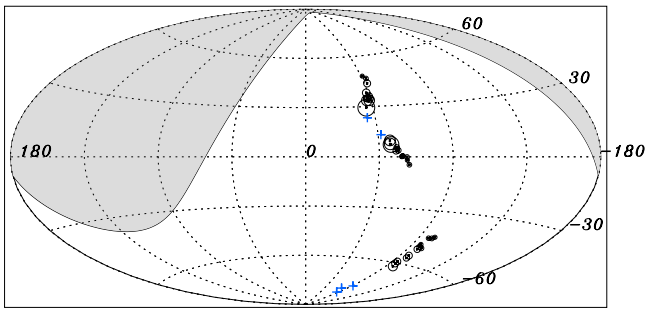

Figure 6. Observed multiplets with 10 or more events in galactic coordinates [14]. The size of the circles is proportional to the energy of the event. Plus signs indicate the positions of the potential sources for each multiplet.

isotropic distribution at least one 12-plet is 6%. No significant evidence for the presence of correlated multiplets is found.

6. CONCLUSION

We reviewed several independent anisotropy analyses recently published by the Pierre Auger Collaboration. At energies in the EeV range, possibly probing galactic cosmic rays, no significant anisotropy has been found. An intriguing behavior of the right ascension phase has to be confirmed by more data. The search for neutron sources, presented as a blind search and a targeted search, gives constraints on models of galactic sources. At high energies, the correlation analysis above 55 EeV has been updated, showing a correlation fraction smaller than earlier estimates, but larger than the isotropic expectation. A search for multiplets induced by coherent extragalactic magnetic fields shows no significant excess.

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