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New results from the Pierre Auger Observatory

G. Matthiae on behalf of the Pierre Auger Collaboration(*)
Università and INFN, Sezione di Roma "Tor Vergata" - Rome, Italy

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Summary. — Recent results from the Auger Observatory on the energy spectrum of high-energy cosmic rays and on the search for correlation with extragalactic objects are presented and discussed. The excess of high-energy events with arrival direction pointing to the region of Centaurus A is discussed in some detail.

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1. – The Auger Observatory

The Auger Observatory [1] is located in a flat region called "Pampa Amarilla", near the small town of Malargüe in the province of Mendoza (Argentina) at the latitude of about 35° S and altitude of 1400 m above sea level. The Observatory is a hybrid system, a combination of a large surface array and a fluorescence detector.

The Surface Detector (SD) is a large array of 1600 water Cherenkov stations spaced at a distance of 1.5 km and covering a total area of 3000 km^2. Each SD station is a plastic tank of cylindrical shape with size 10 m^2 × 1.2 m filled with purified water. The surface detector measures the front of the shower as it reaches ground.

The Fluorescence Detector (FD) consists of 24 telescopes located in four stations which are built on the perimeter of the site. The telescopes measure the shower development in the air by observing the fluorescence light. The field of view of each telescope is 30° × 30°. Attenuation of the fluorescence light along the path from the shower to the telescopes is measured systematically with atmospheric monitors.

2. – The energy spectrum

The Auger data on the energy spectrum which are presented here refer to showers with zenith angle below 60° because the analysis of inclined showers requires a more complex and sophisticated treatment. It is experimentally known that most primaries

(*) A full list of the authors of the Auger Collaboration together with their affiliation can be found at `http://www.auger.org/archive/authors_2010_10.html`

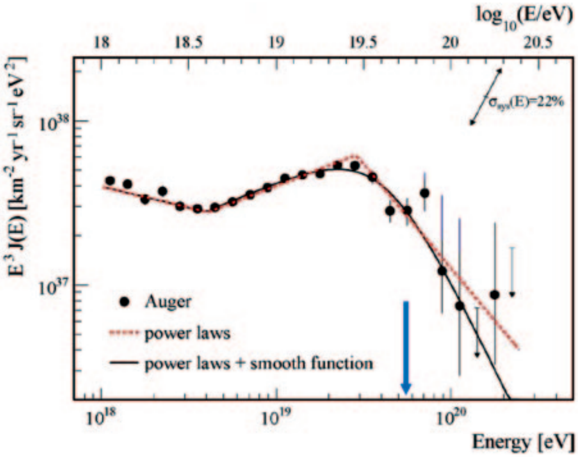

Fig. 1. – (Colour on-line) The energy spectrum of primary cosmic rays, presented as flux multiplied by the power E^3 is shown as a function of energy. The systematic uncertainty on the energy scale of 22% is also indicated. The blue arrow is explained in sect. **3**.

are nuclear particles. In the energy region 10^{18}–10^{19} eV no photon candidates were found and an upper limit of 2–3% for the photon fraction has been published [2] by the Auger Collaboration.

Two different methods have been used by the Auger Collaboration to measure the energy spectrum of primary cosmic rays [3, 4].

- The first method is based on the events observed by the Surface Detector. For primaries with nuclear interactions the efficiency of the SD saturates at $E \sim 3 \times 10^{18}$ eV and above this energy is independent of the primary composition. The exposure is determined only by the extension of the surface array, a geometric quantity which can be calculated at the 3% level.

- The second method is based on the hybrid events, *i.e.* on the events which have been detected at the same time by both the SD and the FD. The minimum energy reachable with hybrid events, $E \sim 10^{18}$ eV, is substantially lower than that of the SD spectrum.

The energy calibration [5], as based on the FD calorimetric measurement, is the same for both methods and therefore the SD and the hybrid spectrum can be combined together after appropriate unfolding. The result [4], obtained with an exposure of about 13000 km^2 sr y, is shown in fig. 1.

The spectrum clearly exhibits two features that appear as two breaking points: the ankle around 4×10^{18} eV and the suppression above $\sim 4 \times 10^{19}$ eV. This suppression near the end of the spectrum agrees with the expectations from the Greisen, Zatsepin and Kuz'min prediction, which is known as the GZK effect [6] and was already observed by the HiRes Collaboration [7]. A simple way of describing the energy dependence of the spectrum in the three regions separated by the two breaking points is provided by a three power law fit (fig. 2) with form $E^{-\gamma}$. In the fit the two values of the energy where the spectral index γ changes are also left as free parameters.

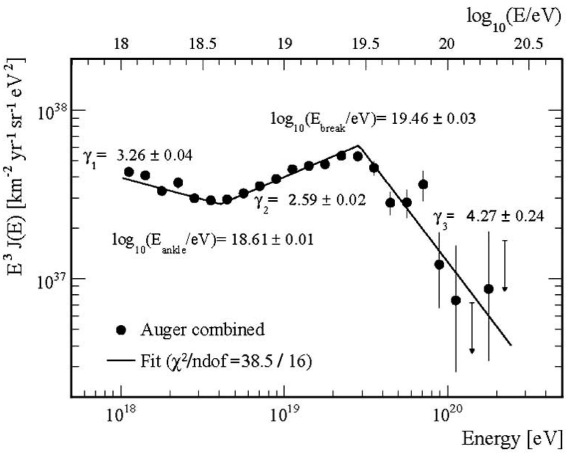

Fig. 2. – Results of the three power law fit in the three energy regions separated by E_{ankle} and by the GZK break. Numerical values of the fitted parameters are also shown with their uncertainties.

The GZK effect is due to the interactions of the cosmic rays with the low energy photons of the Cosmic Microwave Background. Protons with energy above the threshold for photoproduction of pions ($\sim 4 \times 10^{19}$ eV) lose energy, about 15–20% per interaction, as they travel in space. The value of the energy where an integral power law spectrum would be reduced to one half is $\sim 5.5 \times 10^{19}$ eV [8]. A consequence of GZK is that protons of very high energy may come only from distances within the GZK horizon or GZK sphere as shown in fig. 3. Most of the particles observed at the Earth with energy above $\sim 5 \times 10^{19}$ eV must have come from sources within less than about 200 Mpc.

Production of electron-positron pairs is less effective than pion photoproduction in terms of energy loss. This process is predicted [9] to be responsible for the ankle, *i.e.* the

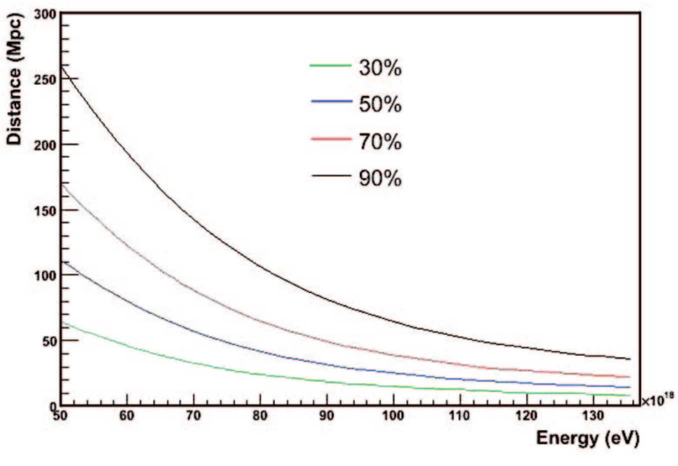

Fig. 3. – The radius of the GZK sphere for protons as a function of the observed energy. The lines correspond to the different fractions of the total number of events as indicated in the inset.

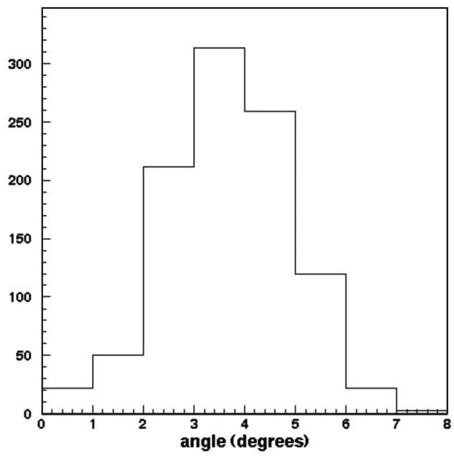

Fig. 4. – Calculation of the deflection of 6×10^{19} eV protons in the galactic magnetic field [11]. For the incoming directions, isotropic distribution is assumed.

shallow minimum (or "dip") at $E \sim 4 \times 10^{18}$ eV. However, according to a different interpretation, this structure may signal the transition from galactic to extragalactic origin. For nuclei, in addition to pion photoproduction, nuclear photodissociation is relevant. While light nuclei are easily broken, it seems that the effect of the interaction with the background electromagnetic radiation for iron nuclei is similar to that for protons [10].

3. – Correlation with extragalactic objects

The observed suppression near the end of the spectrum where the GZK mechanism is expected, is clear indication of the extragalactic origin of the particles in that energy region. Therefore the next obvious step is to try to identify the sources of these particles.

Relevant quantities in this search are discussed below.

- The expected deflection in the galactic magnetic field was evaluated using current models and found to be around 4 degrees [11] for protons of energy of 6×10^{19} eV as shown in fig. 4. On the other hand, deflection by the incoherent extragalactic magnetic fields should be smaller.

- The accuracy of reconstruction of the direction of the showers depends on the number of activated stations of the SD as shown in fig. 5. A vertical shower of energy 10^{19} activates 7-8 stations on the average and therefore showers with energy above 10^{19} are reconstructed with accuracy better than one degree.

According to the previous discussion, one may expect that in the very high-energy region the observed direction of arrival corresponds to the direction of the source within a few degrees. It is known that the distribution of matter within the GZK sphere (radius of about 200 Mpc for energies above 5×10^{19} eV) is not homogeneous. There is an accumulation in the region of the supergalactic plane and therefore anisotropy is expected in the distribution of the arrival directions.

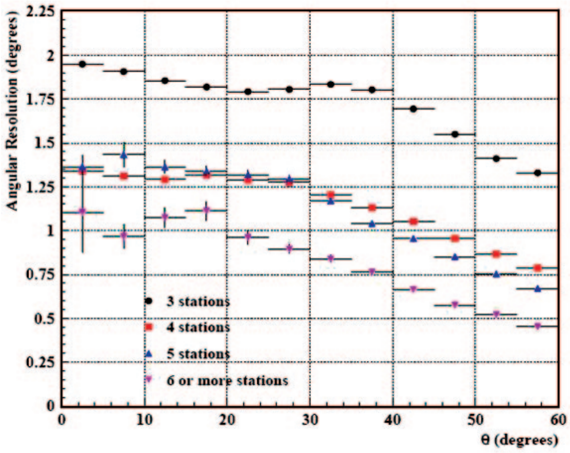

Fig. 5. – The accuracy of the angular reconstruction of the shower direction as a function of the zenith angle for different numbers of activated stations.

The Auger Collaboration has published an extensive search for correlation of the high-energy events with known astrophysical objects. This study started early in 2004 [11] and the results have been updated recently [12]. The arrival direction of the events was compared to the direction in the sky of the galaxies with active nucleus (AGN) listed in the catalog of ref. [13]. Quasars, Lac objects and active galaxies were considered. Maximum correlation was found for $E > 55\,\text{EeV}$, for distances less than 75 Mpc and for the angular scale of 3.1°.

Results of a new study of correlations [12] using the Swift-BAT hard X-ray catalog [14] which is an all-sky survey in the hard X-ray band are presented here. With respect to optical surveys, the results from the hard X-ray band are less affected by bias due to absorption. A sample of 373 AGN galaxies was selected from the Swift-BAT catalog requiring distances less than 200 Mpc.

A cross-correlation analysis between the arrival directions of the events and the positions in the sky of the galaxies of this sample was performed. For each event the arrival direction forms a pair with the selected objects in the catalog with separation angle Ψ. The actual number of pairs $N_p(\Psi)$ with separation less than Ψ was calculated and also the corresponding quantity $N_p(\Psi)_{\text{iso}}$ derived from simulations assuming isotropic distribution.

The relative excess with respect to isotropic expectations of pairs having angular separation less than Ψ, as given by the expression

$$N_p(\Psi)/N_p(\Psi)_{\text{iso}} - 1,$$

is a good estimator of departure from isotropy. The result using all presently available statistics corresponding to 69 events with $E > 55\,\text{EeV}$ is shown in fig. 6.

It is clear that the events in the high-energy region have a distribution which is departing from isotropy at the level of about 3 standard deviations. On the contrary similar plots, presented in fig. 7 for lower energy intervals are consistent with isotropy. The blue arrow shown in fig. 1 is meant to indicate approximately the separation between isotropy and the anisotropic regime that emerges as the energy increases, in the region

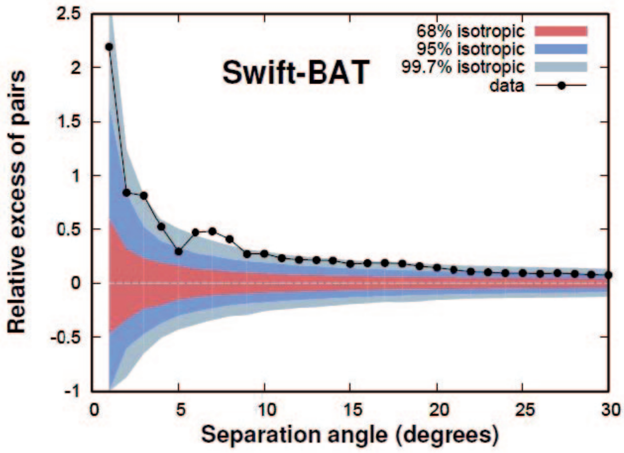

Fig. 6. – Cross correlation between the directions of the 69 events with $E > 55$ EeV and the position of the AGN from the Swift-BAT catalog which lie within 200 Mpc. The bands in the plot contain the dispersion for one, two and three standard deviations, respectively, of simulated sets of the same number of events assuming isotropic distribution.

of the GZK suppression. One might speculate that the observed isotropy at the energies of fig. 7 is a consequence of larger deflections in the magnetic field.

A sky map in galactic coordinates showing the 69 events with energy larger than 55 EeV as black dots is presented in fig. 8. The brown coded region describes the distribution of the AGNs from the Swift-BAT catalog within 200 Mpc smoothed with angular scale of 5 degrees to account for the estimated deflection by magnetic field and the angular resolution.

The region with the largest over-density of arrival directions for the 69 events with $E > 55$ EeV, as estimated by the excess above isotropic expectations in circular windows, is centered at galactic coordinates $(l, b) = (-46.4°, 17.7°)$. There are 12 events with directions inside a window with radius 13° centered in that location, where 1.7 is the isotropic expectation. The centre of this region is only 4° away from the location of the radiogalaxy Cen A, which is the closest AGN (3.8 Mpc away from us) and it is about 7°

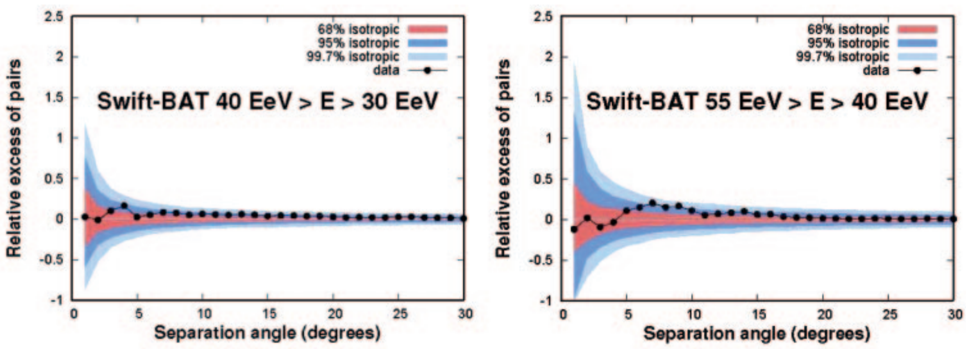

Fig. 7. – Same plots as fig. 6 for two different lower energy intervals.

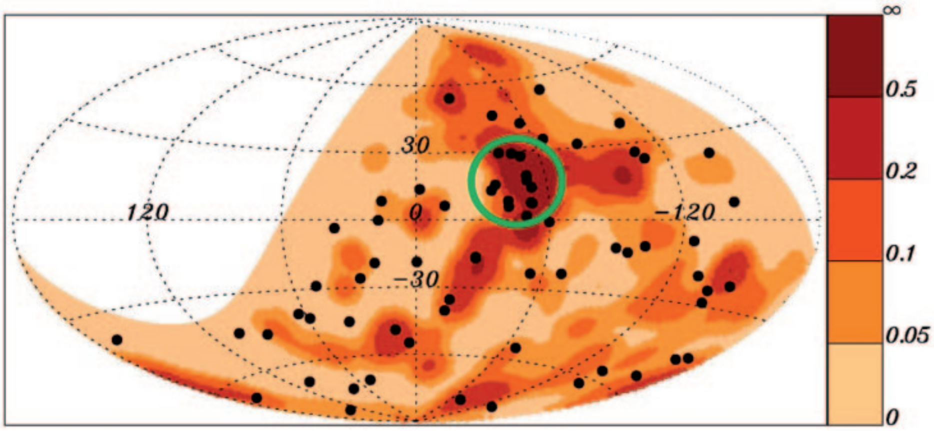

Fig. 8. – (Color online) Plot in galactic coordinates of the events with $E > 55\,\text{EeV}$ and the distribution of AGNs within 200 Mpc from the Swift-BAT catalog coded in brown color. The white region of the sky is not accessible from the Auger Observatory. The green line encircles the region with maximum excess of the number of events with respect to isotropic distribution.

from the direction of the Centaurus cluster which is much further away (40–50 Mpc) but still within the GZK sphere. It has been suggested [15] that most likely the particles in this angular region do not come from Cen A but from the Centaurus cluster.

The cumulative number of events with $E > 55\,\text{EeV}$ and directions within a cone with variable aperture and axis on the direction of Cen A is shown in fig. 9. The largest departure from isotropy is given by the presence of 13 events with arrival directions in a circular window of 18°, while 3.2 events would be expected if the flux were isotropic.

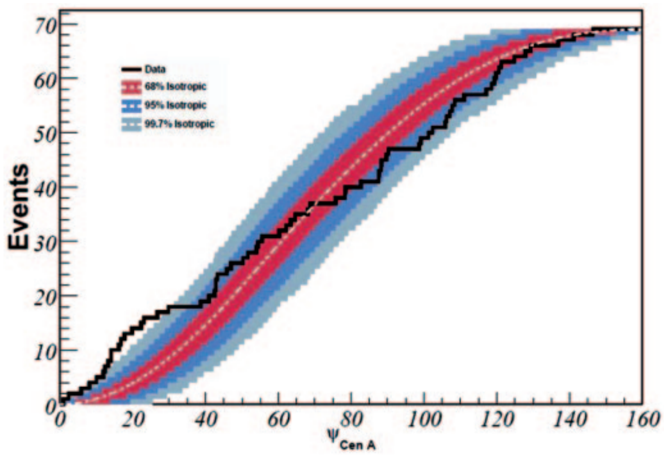

Fig. 9. – (Color online) Cumulative distribution for the events with $E = 55\,\text{EeV}$ as a function of angular distance from Cen A. The colored bands correspond to isotropy and have the same meaning as in fig. 6.

4. – Conclusions

In spite of the still low number of events, one may draw the following conclusions.

- There is clear hint for departure from isotropy for the events at the very end of the spectrum, in the GZK suppression region. The angular distribution of these events bears resemblance with the distribution of the AGNs which lie within the GZK horizon.
- The excess in the region of Centaurus appears to be statistically significant. In that region there is accumulation of the high energy events and also over-density of the AGNs.
- The sample of events useful for this new "astronomy" with cosmic rays is limited to a narrow window between the lower energy region of isotropy and the end of the spectrum. In spite of this limitation present observations are providing the first identification of sources of the extragalactic cosmic rays.

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