Results of the Pierre Auger Observatory on High Energy Cosmic Rays

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Abstract. The Pierre Auger Observatory is a hybrid detector comprising water tank detectors covering an area of 3000 km^2 and fluorescence detectors located in 4 stations surrounding that area. The Pierre Auger Observatory has been in operation for the past few years while its components were being gradually assembled and deployed on the field. In spite of the limited acceptance the data which have been gathered have already delivered interesting results on High Energy Cosmic Rays. This paper reviews the most interesting results published by our collaboration so far, including limits on high energy photons and neutrino fluxes, the spectrum, the anisotropy of Ultra High Energy Cosmic Rays and their correlation with extragalactic objects.

1. Introduction

Cosmic rays provide the source of the most energetic particles known to scientists with energies reaching values far beyond those attainable at our largest colliders. Our knowledge on Ultra High Energy Cosmic Rays (UHECR) is still limited since the flux of cosmic rays decreases with energy and direct detection of sufficient numbers is not feasible. Only vast arrays of detectors capturing information of the Extensive Air Showers (EAS) produced by the primary cosmic ray particles can gather enough statistics over long periods of time. There are currently different models trying to explain the formation of those particles and basically all of them fall into two different categories : acceleration and *Top-Down* models. Acceleration mechanisms assume that those cosmic rays are accelerated within astrophysical objects of the appropriate size and magnetic field before coming to the earth [1]. In *Top-Down* models the cosmic rays are produced in decays of supermassive particles or topological defects. As we will see, our results tend to discard the latter possibility.

The Pierre Auger Observatory can be considered as the biggest calorimeter in the world since it makes use of an enormous portion of atmosphere as sensitive material. The particle showers produced by high energy cosmic rays interacting in air are detected with the help of two different techniques: surface water tanks recording Cerenkov light produced by the remnants of the showers at ground level and fluorescence detectors which track the evolution of the shower as it develops. These two independent detection techniques allow to extract optimum information of those uncommonly high energetic particles coming from outer space. There are currently more than 1600 high purity water tanks deployed which include 3 photomultiplier tubes that transform the Cerenkov light into a measurable electrical signal. The detectors are placed according to a triangular pattern with a distance of 1.5 km between them. This array of

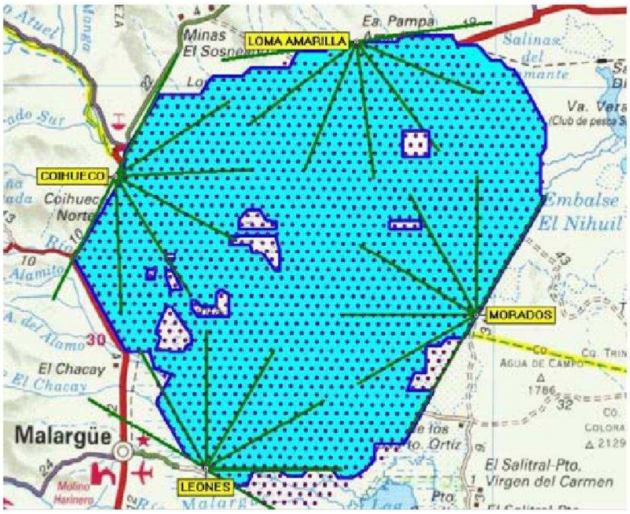

Figure 1. The observatory is located near Malargüe, in the province of Mendoza, Argentina. The dots represent the position of the water tanks. The four FD stations are named within yellow coloured rectangles. The azimuthal coverage of each telescope is represented with green lines

detectors is collectively known as the *Surface Detector* (*SD*) [6]. The *Fluorescence Detector* (*FD*) consists of 4 stations overlooking the area covered by the water tanks with 6 fluorescence telescopes each. Those telescopes contain mirrors covering 30^0 in azimuthal and zenithal angles which reflect the fluorescence light emitted by excited N_2 molecules onto an array of 22×20 photomultipliers. The layout of the tanks and the telescope stations is visible in Figure 1. The properties and performance of prototype instruments can be found in the following reference; [5]

1.1. Event Reconstruction
The position and the timing of the signals of the SD tanks allow to make a fit to the shower front of the cascade of particles which derives the zenithal and azimuthal angles of the incoming primary particle. Even for the lowest energy events which can be triggered by our detector (10^{18}eV) the angular resolution is smaller than a couple of degrees and as soon as the energy increases and more stations are involved in the reconstruction the resolution becomes roughly 1 degree or even less. The energy of the shower comes from another fit; this time it involves the Lateral Distribution Function (LDF) of the tank signals and their distances to the core of the shower. The fitted parameters are the core position and the expected signal value at 1000 meters from the core, S_{1000}. The choice of that distance guarantees the smallest fluctuations in the extracted signal parameter. The next step in order to compute the energy is to normalize the signal obtained at the measured zenithal angle to a given reference angle since there is a clear dependence of the signal with that angle. The chosen value is 38^0 which is the median of the zenithal distribution. The procedure to perform this normalization is called the Constant Intensity Cut (CIC) [4]. Assuming a nearly isotropic flux of cosmic rays beyond a given energy threshold it is easy to establish the normalization factors to estimate S_{38}. The last step to obtain the energy of the primary particle is the correlation of the value of S_{38} with the nearly calorimetric, model independent energy measurement of the FD detector. We use hybrid events where information of the shower is recorded in both detector systems, SD and FD. The dispersion

of the SD estimates with respect to the FD energy values is about 20%.

The reconstruction of the arrival direction of the cosmic ray in the FD makes use of the position of the photomultipliers within the array and the timing of the signals recorded on those hit by reflected fluorescence photons. The angular fit does not precisely fix all the parameters and we need the timing of a tank from the SD detector in order to decrease the resolution from several degrees down to about 0.5^0. The energy estimate comes from a fit with a Gaiser-Hillas function [3] to the Longitudinal Shower Profile (LSP) obtained with the amount of signal collected on the PMTs. This measurement relies fully on the calorimetric properties of the atmosphere and not on hadronic models and is, therefore, quite accurate.

The hybrid approach of our detector provides obvious advantages. It allows a very precise determination of the energy and arrival direction of the cosmic primaries; we are able to calibrate the energies of the water tanks with the help of hybrid events and the timing of the tanks improves significantly the angular resolution of the FD. It is also easier to study systematic effects since both detectors provide totally independent measurements.

2. Energy spectrum

The spectrum of the cosmic rays follows approximately a power law with a negative index which is not completely uniform. When the energy of the primary reaches a value of $\simeq 4 \cdot 10^{18}$eV the index becomes smaller (*ankle*). The most common explanation is the onset of an extragalactic component. At even higher energies $E \simeq 6 \cdot 10^{19}$eV the GZK (Greisen-Zatsepin-Kuzmin) effect [2] should take a dominant role. It is the consequence of the ubiquitous presence of the Cosmic Microwave Background in outer space. The interaction of protons with the CMB at those energies produces pions whereas heavy nuclei disintegrate at even lower energies. Therefore an abrupt decrease of the flux of UHECR is expected unless their origin is considerably closer than the interaction length ($\lambda \sim 50$ - 100 Mpc) for these processes involving the CMB.

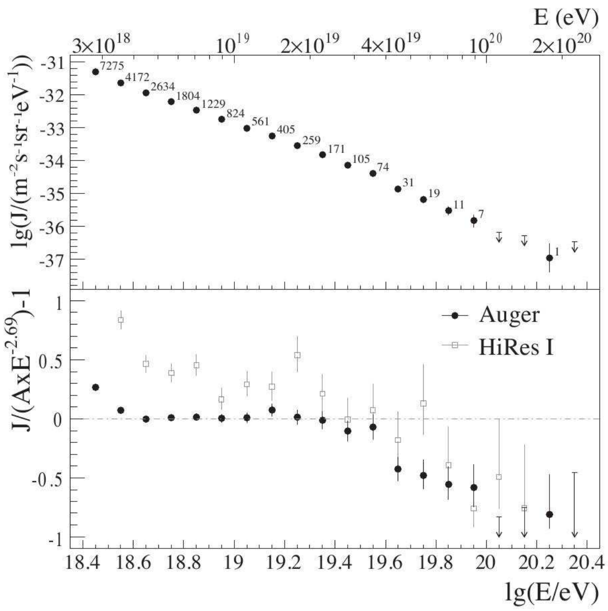

Figure 2. In the upper plot we present the flux and the number of events corresponding to each energy value. In the lower plot we show the spectrum for HiRes I and Auger normalized to a spectrum with a power index of −2.69.

Results presented by previous experiments were contradictory. AGASA, an array detector, obtained a flux which differed in the shape and the absolute scale from the flux measured by HiRes, a fluorescence telescope; the flux values measured by AGASA were higher and no evidence of the GZK-effect was noticeable [13] whereas HiRes observed a steepening of the curve at GZK cutoff energies [14]. The spectrum obtained by the Pierre Auger Observatory (see Figure 2) basically agrees with the recent results of HiRes establishing new evidence of the expected GZK effect [7].

3. Photons

Photons of the energy range studied in our experiment penetrate deeper in the atmosphere than protons or nuclei. It is easy to prove that the delay of the signals induced on the tanks by the particles of the shower front decreases with the height of the production point. Therefore, photon showers give higher delays on the stations as compared to proton or nuclei induced showers. This is related to the curvature of the shower front which can be extracted from a fit to the trigger times of the SD tanks. On the other hand, the time spread of the signals on a given tank corresponding to particles generated at lower heights is bigger than the spread for particles appearing at higher altitude. This, combined with the fact that showers induced by photons have a lower quantity of muons which are produced high in the atmosphere, help to establish selection criteria based on the risetime (time difference between 10% and 50% of integrated signal) of the ADC traces recorded in the water tanks.

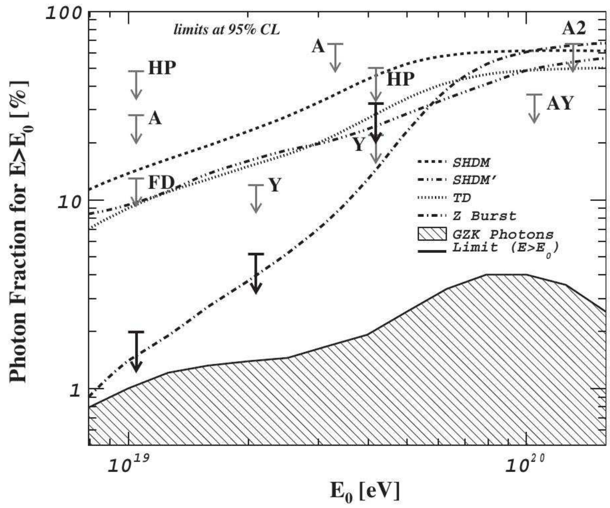

Figure 3. Photon fractions at 95% C.L. for different experiments and models; HP: Haverah Park, A1 and A2: AGASA, AY: AGASA-Yakutsk, Y: Yakutsk, FD: Auger hybrid and black arrows: Auger SD. The striped area represents the expectation for GZK photons.

The variables chosen for our selection cuts are the radius of curvature R and the expected risetime value at a distance of 1000 meters from the core of the shower $t_{1/2}(1000)$. The latter variable comes from a fit to the risetime values of the tanks corrected by their internal azimuthal angle and the shower zenith angle. Normalized (*pull*) variables involving the photon expectation values and the spread in the distributions are combined into a two-dimensional plot in order to perform a principal component analysis with a selected efficiency of 50%. More details can be found in reference [8].

No candidates were found after applying our selection criteria; thus, limits on the flux and the fraction of photons were calculated at 95% C.L. for different energy ranges. Figure 3 shows the fraction of photons obtained by our collaboration for three different energy values compared to the expectation curves of several models. Many of the Top-Down scenarios for HECR production are rejected with our results.

4. Ultra High Energy Neutrinos

The interaction probability of a neutrino with matter is very low and it can produce a shower anywhere along its path in the atmosphere. If we limit our study to showers which have already traversed a long distance within air, the electromagnetic component should be highly suppressed. This is the case of showers with big zenithal angles initiated by protons and heavy nuclei which are produced close to the point where the particle enters the earth atmosphere. On the other hand, neutrinos interacting deep in the atmosphere will produce a shower with a detectable electromagnetic component, especially in those tanks hit earlier by the shower front. The Pierre Auger Observatory is studying so called *horizontal* showers ($\theta > 60^0$) where the time spread of the *early* tanks signals is high according to the risetime and falltime ($50\% - 90\%$ of the signal) observables. This analysis is still in progress. Our collaboration has been also looking for τ neutrinos interacting with the crust of the earth or the mountains surrounding the SD area [11]. If they undergo charged-current interactions they can produce τ particles that may travel as far as 10 km before producing a shower which is nearly horizontal. The event selection for neutrino showers includes a cut on the time spread of signals within the FADC traces of the water tanks. It requires a certain elongation pattern of the triggered tanks by assigning a length and a width to the event and restricting its ratio. In addition, it is assumed that the event travels horizontally at a velocity which is close to the speed of light. The measured value is an average obtained for pairs of triggered stations. The RMS of their distribution also helps to discard non neutrino events.

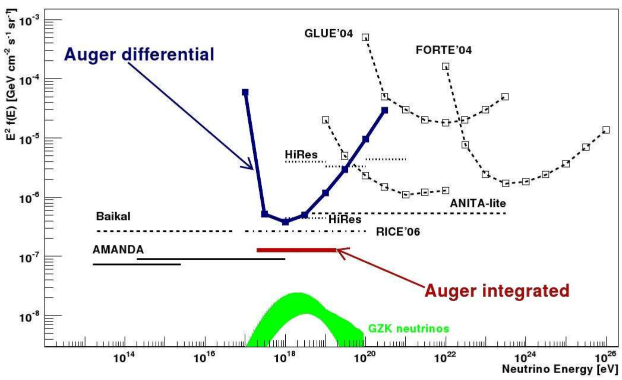

Figure 4. Limits on integrated and differential fluxes of high energy neutrinos for different experiments including those obtained by the Pierre Auger collaboration.

The selection criteria retain 80% of neutrino showers while no background event is kept. No candidates have been found until now, so we have established limits on the differential and integral neutrino fluxes. Those limits pose a big constraint on certain *Top-Down* models, even rendering some of them invalid. As can be seen in Figure 4 [18], our observatory may be capable of observing GZK neutrinos produced in the collisions of CRs with the CMB in the near future. The limit derived from our study on the diffusive neutrino flux in the energy range $2 \times 10^{17} < E < 2 \times 10^{19}$ eV is $E_\nu^2 dN_{\nu_\tau}/dE_\nu < 1.3 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1}.

5. Large scale anisotropy of HECRs

The Galactic Centre (GC) harbors several objects which could be sources of ultra high energy cosmic rays and it is therefore an interesting region if we look for anisotropies in the HECR flux. It is even more attracting if we consider that previous experiments reported excesses in areas located close to it. In particular, AGASA observed a 4.5σ excess in the energy range $10^{18} - 10^{18.4}$eV in a 20^0 radius area close to the GC [15] [16] and SUGAR measured a 2.9σ flux excess in the range $10^{17.9} - 10^{18.5}$eV in a smaller region with a radius of 5.5^0 centered at a different point [17].

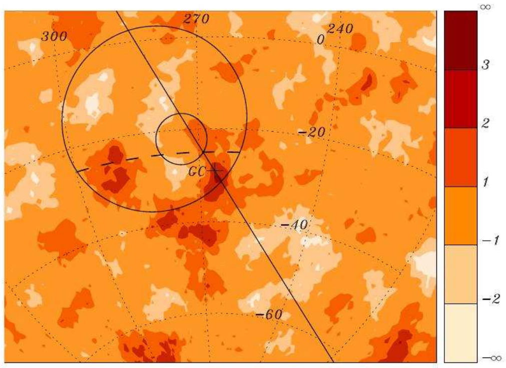

Figure 5. Map of overdensity significances around the galactic center. The regions where AGASA and SUGAR found excesses are also shown in circles.

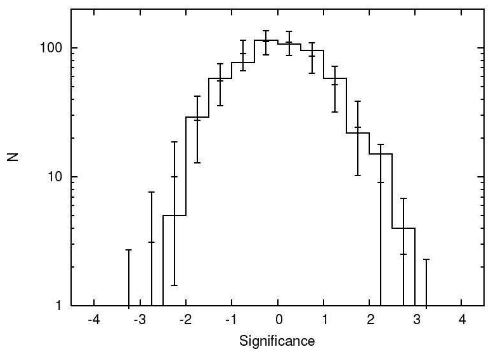

Figure 6. Histogram of overdensities (line) with superimposed isotropic expectations (average and 2σ bounds).

In our analysis [12] we considered the events with reconstructed energies in the range chosen by SUGAR. To search for anisotropy in the HECR flux, we compare our data to an estimate of the flux expected from an arrival direction distribution that is isotropic, but modified to account for the modulations of the exposure with right ascension as the array grew during construction. In Figure 5 we present the significances of the overdensities in circular windows of 5^0 radius. The distribution of observed overdensities is compared to the expectations for an isotropic flux in Figure 6. Our data is completely consistent with statistical fluctuations of an isotropic sky.

6. Anisotropy of UHECRs and their correlation with Active Galactic Nuclei (AGN)

The source of the UHECRs has been a topic of great interest since their discovery and according to acceleration models only certain objects with high magnetic fields covering big enough areas are capable of generating particles at such extraordinary energies. Active Galactic Nuclei are amongst those objects which could be held responsible for UHECR production. The quasars and active nuclei listed in the 12^{th} edition of the Veron-Cetty and Veron catalogue [10] have been used in our correlation study. The catalogue, although thoroughly compiled to include all objects in the literature, can not be considered to be complete, especially near the galactic plane, nor an unbiased sample.

A first scan was conducted with a set of our data (*exploratory scan*) to obtain the values of the angular distance ψ, the maximum redshift z and the minimum energy E_{min} which minimized the chance probability for an isotropic flux. The selection parameters obtained with this *a priori* analysis were applied to future data according to a *running prescription*. This prescription, applied on an event by event basis, was established in order to confirm the anisotropy of the UHECRs. The procedure we followed avoids any penalty factors which would apply in *a posteriori* searches. More information on this can be found in references [19] and [9].

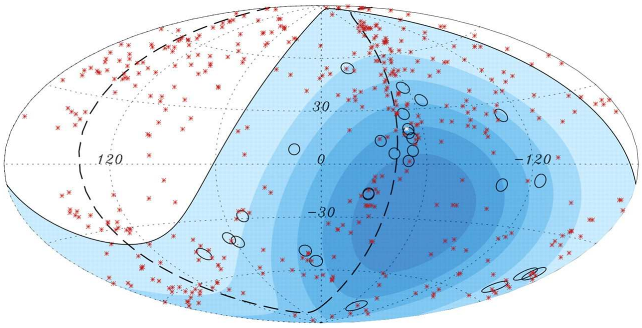

Figure 7. Aitoff projection of the celestial sphere in galactic coordinates. The positions of the AGNs with distances smaller than 71 Mpc and the 3.2^0 circles around the selected events are marked. Colors indicate equal exposure.

The analysis of the whole data set derived the following numbers for the maximum correlation significance: $E_{min} = 57$ EeV, $z_{max} = 0.017$ corresponding to distances $\lesssim 71Mpc$ and $\psi = 3.2^0$. The angular distance is bigger than the resolution of our detector for cosmic rays with energies beyond 10^{19}eV (about 1^0 or lower) but we have to take into account the presence of magnetic fields in the trajectory of the rays. With the selected parameters we find that 20 out of 27 cosmic ray events correlate with an AGN where only 5.6 are expected for an isotropic flux. It is worth mentioning that 5 out of the seven which do not correlate are within 12^0 of the galactic plane where, on the one hand, the data of the VC-V catalogue is less reliable and on the other hand, the magnetic fields are stronger. Figure 7 shows the position of the correlated cosmic ray events and that of the AGNs within the obtained maximum distance.

In any case, the scientific claim of the Pierre Auger Collaboration is that the highest energy cosmic rays are not isotropic but in spite of the observed correlation we can not claim that the sources of those rays are, actually, AGNs. They could be the sources but they may be just tracers for the real sources since the spatial distribution of those objects agrees well with that of other extragalactic objects. It is important to notice that the calculated minimum energy and maximum distance lie within the GZK effect expectations. The fact that the angular distance is relatively small would favour that the highest energy rays are protons.

7. Conclusions

The Pierre Auger Observatory is an enormous air calorimeter which has been collecting data on UHECRs with a growing array of water tanks and fluorescence telescopes for several years and now is finishing its deployment. The data acquired so far has already allowed to improve our knowledge on several topics related to high energy cosmic rays. The spectrum of the cosmic rays above 10^{18} eV shows an abrupt decrease above 60 EeV confirming the expected GZK effect. Our collaboration has been able to establish very good limits on neutrino and photon fluxes which discard many *Top-Down* models. Additional data should provide evidence for photons and neutrinos produced in the interaction of protons and nuclei with the CMB. There is no evidence of anisotropy of HECR with energies in the range $10^{17.9} - 10^{18.5}$ eV around the galactic center, whereas UHECR rays with energies greater than 60 EeV show a clear anisotropic origin. Using a catalogue of extragalactic objects containing a compilation of AGN we have observed a correlation with our highest energy events,but this does not establish that AGN themselves are the sources. The significance of the correlation is maximized for distances and energies which agree with the existence of the GZK cut-off.

The successful completion of the Observatory is an important milestone which makes us confident that our laboratory will be able to continue producing interesting results in the future. Members of the collaboration are already working on the deployment of a test array in the vicinity of Lamar (Colorado) which will be the starting point for the northern hemisphere Observatory. It will cover the areas of the sky not reachable with the southern hemisphere Observatory and it will, obviously, increase our statistics. Thus, it is evident that there is a bright future ahead of us in the field of High Energy Cosmic Rays.

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