

Astroparticle physics: new results from the Pierre Auger Observatory and future plans

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The Pierre Auger Observatory is an international effort of research groups from 18 countries to provide measurements of Extensive Air Showers (EASs) initiated in the upper atmosphere by the Ultra High Energy Cosmic Rays (UHECRs), extraterrestrial subatomic particles with energies above 10^{18} eV. The southern site, located in Province of Mendoza, Argentina, was completed in 2008 and is now fully operational. Data has been recorded since the beginning of the construction phase, in 2004. The observatory consists of a giant hybrid detector using an array of more than 1600 water Cherenkov tanks spread over an area of 3000 km², overlooked by a set of 24 air fluorescence telescopes, placed in four buildings on the array boundaries. The recent results and future plans of the observatory are presented in this paper.

Key words: Ultra high energy cosmic rays, Pierre Auger Observatory, energy spectrum, composition, anisotropy.

*5th International School on Field Theory and Gravitation,
April 20 - 24 2009
Cuiabá city, Brazil*

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†The author is thankful to FAPESP, CNPq and CAPES for the financial support.

1. Introduction

The Pierre Auger Observatory [1], [2] is the world's largest array of detectors exploring the energy spectrum, arrival directions distribution and composition of cosmic rays above 10^{17} eV. The Ultra High Energy Cosmic Rays (UHECRs) still are an important puzzling mystery of nature, despite the progresses that cosmic ray physics had seen in the last decades. UHECRs travel the Universe and reach the Earth's atmosphere with macroscopic energies. Above ~ 60 EeV¹, due to their interactions with the cosmic microwave background photons, the UHECRs can produce pions and develop a suppression in their energy spectrum, the Greisen-Zatsepin-Kuzmin (GZK) cutoff [3] [4]. As a consequence of the energy loss in the pion production, the UHECRs sources should be restricted to our cosmological neighborhood, at distances up to 100 Mpc (GZK horizon).

The first observation of cosmic rays with energies above 50 EeV was done in 1962 [5]. Since then, several events with energy above 10^{20} eV have been observed and reported [6]. However, the previous arrays, with collecting area smaller than 100km^2 , did not provide enough statistics, due to the extremely low flux at such energies: 1 event per century per km^{-2} above 10^{20} eV. Thus vast areas must be instrumented to accumulate enough number of events during a practical period. The Pierre Auger Observatory combines a surface detector array, with a large collecting area of 3000 km^2 , to record the lateral distribution of charged particles at ground level and a fluorescence detector to record the longitudinal light profile of showers in the atmosphere. This approach is very useful because one takes advantage of two complementary techniques. UHECRs generate air showers with over 10^9 particles at their maxima. The particles that reach ground level

are spread over areas of about tens of km^2 permitting the continuous sampling of the showers by the surface detector. The faint fluorescence light that is generated by the excitation of atmospheric nitrogen is summed over the billions of shower particles enabling to track them during dark nights.

The Pierre Auger Observatory was designed and built to answer open questions in the field of astroparticle physics. Its scientific objectives are to understand the nature, origin and propagation of UHECRs. The southern site is completed and taking data with an aperture greater than $7000\text{km}^2\text{sr}$ at 10^{19} eV providing high statistics. The collaboration intends to build another site in the northern hemisphere to fully cover the sky with uniform exposure.

2. The observatory

The Pierre Auger Observatory is a hybrid giant detector using two main techniques to observe Extensive Air Showers (EASs). Water Cherenkov tanks composing the Surface Detector (SD) and fluorescence telescopes composing the Fluorescence Detector (FD). In Fig. 1, the observatory layout by September 2009 is shown. The four FD sites — Leones, Morados, Loma Amarilla and Coihueco — and other facilities — CLF (Central Laser Facility), XLF (eXtreme Laser Facility), BLF (Balloon Launching Facility) and HEAT (High Elevation Auger Telescopes) — are shown.

2.1 The Surface Detector

The SD consists of an array of 1640 water Cherenkov tanks disposed on a triangular grid with 1.5 km spacing and spread over an area of 3000 km^2 . Water Cherenkov tanks have low cost and operate continuously with any kind of weather. They are polyethylene resin tanks filled with 12 tons of ultra-pure water. Three 9 inch photomultiplier tubes are placed inside the

¹1 EeV = 10^{18} eV

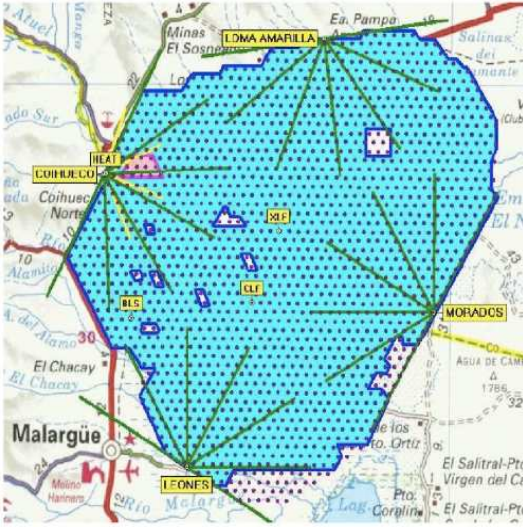


Figure 1: Current layout (Sept. 2009) of the southern site of the Pierre Auger Observatory in Province of Mendoza, Argentina. In light blue is represented the covered area of the deployed tanks. The green lines indicate the field of view of the fluorescence telescopes. Ref.: [7].

tank to detect the Cherenkov radiation emitted in the water. Solar panels are used to charge batteries, which provide all the power the tanks need. Electronics, mounted inside a dome on top of the tank, collect the phototube signals and send the information via antenna to the central station. A GPS device provides accurate timing, so that signals from many tanks can be properly compared.

2.2 The Fluorescence Detector

The FD consists of 24 telescopes overseeing the array of tanks and grouped in 4 buildings at the array border. Each one of the telescopes is composed by a spherical mirror with curvature radius of 340 cm, covering 30° range in azimuth and 2° to 32° range in elevation. The fluorescence light impinges on an array of 440 photomultiplier tubes placed at the focal surface. The system adopts Schmidt optics using an aperture box with 110 cm of diaphragm radius with an external ring of corrector lenses

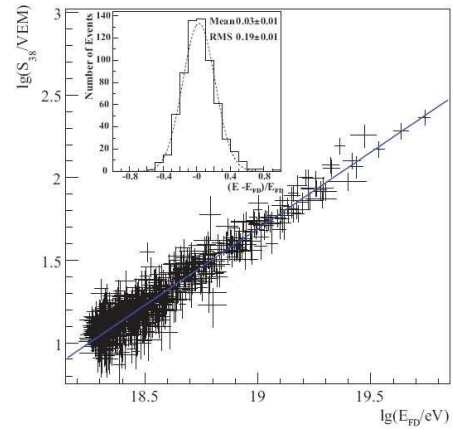


Figure 2: Correlation curve of the SD and FD energies and the fractional difference between each energy estimator. Ref.: [9]

[8] and a band pass filter passing the near ultraviolet band ($300 \text{ nm} < \lambda < 410 \text{ nm}$), which contains the main emission peaks of the nitrogen fluorescence.

The FD telescopes detect the faint fluorescence light emitted by nitrogen molecules in the air when they are excited by EAS particles. To be able to observe it the FD stations operate only in moonless nights with clear weather. Such condition corresponds to about only 10% of the duty time, but this disadvantage is compensated by the generation of the so-called hybrid events, which enable studies of cross-correlation between the two techniques and energy calibrations (see Fig. 2).

3. Recent results

3.1 Anisotropies

Searches for anisotropies at EeV energies in the region of some candidates for UHECRs sources have been done by the Auger collaboration. An attractive candidate is the Galactic Centre (GC) region, since it houses some objects that might be candidates for powerful accelerators: the supernova remnant Sagittarius A East and the very massive black hole asso-

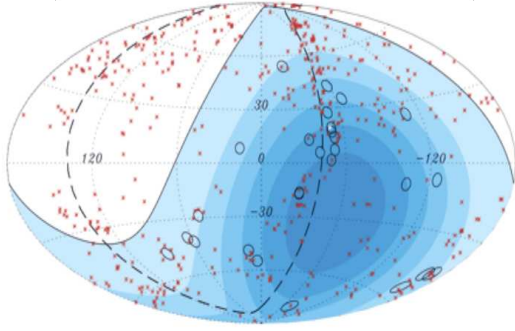


Figure 3: Correlation of UHECRs with energies exceeding $56 EeV$ and the positions of nearby AGNs. Ref: [10].

ciated with the radio source Sagittarius A*, for instance. However, Auger results do not support any excess of cosmic rays coming from the GC. Using the first 2.3 years of data, with energies in the range $10^{17.9} - 10^{18.5}$ eV, the GC region, which is well within the field of view of the observatory, do not show significant excesses for a point-like source or overdensities for larger angular windows (5° radius).

Another important result from Auger is the correlation of the arrival directions of 3.7 years of data of cosmic rays with energy above $56 EeV$ and the positions of the nearest Active Galactic Nuclei (AGNs), see Fig. 3. The arrival directions of the 27 events with highest energies are given by open circles of radius 3.1° . The positions of the 472 AGNs (318 in the field of view) within distances of 75 Mpc (or redshift $z \leq 0.018$) [11] are given by red asterisks. Darker blue indicates larger relative exposure. The observed correlation do not identify sources or astrophysical sites of origin, but suggests that the UHECRs are coming from a GZK horizon. The hypothesis of isotropic distribution was rejected with at least 99% confidence level from a prescribed a priori test. Subsequent update of the analysis of correlation with AGNs, with nearly twice the previous exposure (now $\sim 1.7 \times 10^4 \text{ km}^2 \text{ sr yr} \pm 3\%$), was

done, but it neither strengthens nor does contradict the earlier result.

3.2 Energy spectrum

The energy spectrum above 10^{18} eV is obtained by the combination of SD and FD measurements. SD signals are quantified in terms of a Vertical Equivalent Muon (VEM), a muon traveling vertically and centrally through a tank. Then, the signal of several tanks is fitted to a lateral distribution function to find the VEM at 1000 m, the $S(1000)$ parameter, which is almost proportional to primary energy. And the signal fluctuations are minimized at that distance from the EAS axis. As the primaries have approximately isotropic flux, a constant integral intensity cut [12] is applied because of the decrease in $S(1000)$ with zenith angle θ . The parameter S_{38° is the $S(1000)$ that EAS would have produced had it arrived at the median angle 38° and is an energy estimator independent of θ .

The conversion from S_{38° to energy is done using the “golden hybrids”, i.e. a subset of doubly reconstructed events, independently by SD and FD only. The 661 golden hybrids used in the fit are plotted in Fig. 2, the best fit to the data is the full line and the inset shows the fractional differences between the two energy estimators.

The obtained energy spectrum is shown in Fig. 4 where an overall systematic uncertainty of 22% for the energy scale was estimated. In the plot, the fractional differences between the spectrum and a flux proportional to $E^{-2.6}$ are shown compared to the results obtained by HiRes I. We can see a change in the spectral index near 4 EeV, suggesting the transition to extragalactic component, and a suppression of the flux above 30 EeV indicating a feature like the one expected for the GZK cutoff.

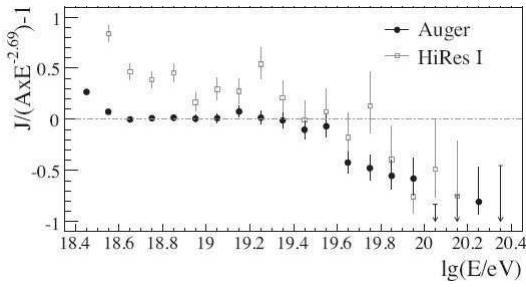


Figure 4: Auger energy spectrum compared with HiRes I and a given power law ($\propto E^{-2.6}$). Ref.: [9]

3.3 Mass composition

The depth at which the EAS reaches its maximum size (X_{max}) and the width of the X_{max} distribution may both be correlated with the cosmic ray mass composition. For example, proton initiated showers develop their maxima deeper into the atmosphere and have wider X_{max} distribution than those initiated by heavier nuclei. Thus, the FD can be used to measure the elongation rate, i.e. the dependence of X_{max} on the energy. The Auger results for the elongation rate are shown in Fig. 5 together with what one would expect from the high energy hadronic models. In Fig. 5, are also given the SD parameters $X_{AsymMax}$, the position of maximum of the risetime asymmetry, and $\langle \Delta_i \rangle$, the deviation for each tank of the measured risetime from a function of the core distance (r) and zenith angle (θ) at 10^{19} eV. They are both expected to be larger for showers developing deeper in the atmosphere. We can see a tendency towards heavier or mixed composition for higher energies. However, additional data for the hadronic interactions in the highest energies are needed.

4. Future plans

The construction of the southern Pierre Auger Observatory is completed since mid 2008, but the site is still being instrumented with several enhancements. Three additional fluores-

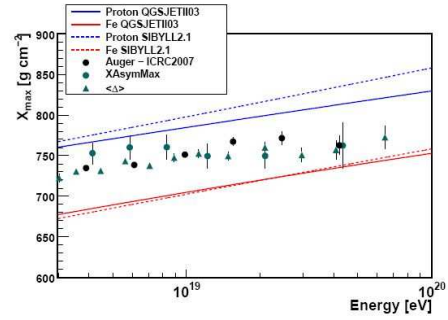


Figure 5: Comparison of the dependence on the energy of X_{max} to the predictions of hadronic interaction models. Ref.: [13]

cence telescopes with field of view from 30° to 58° of elevation form HEAT (High Elevation Auger Telescopes) near Coihueco site. They are intended to measure showers with X_{max} higher in the atmosphere. Near the same site, 85 pairs of a water Cherenkov tank and a buried muon counter arranged at 750 m and 433 m array spacings form AMIGA (Auger Muons and Infill for the Ground Array). Both are designed to improve the quality of EAS reconstruction in the energy region $10^{17} - 10^{19}$ eV, motivated for the study of the behavior of cosmic rays composition in the transition from galactic to extragalactic components. Another project near the infill array is AERA (Auger Engineering Radio Array), an array of radio antennas of about 20km^2 to study and detect coherent radio emissions from EASs in the atmosphere. There are plans yet for growing the Auger southern array in neighboring sites, to further increase the exposure and number of events of the highest energies detected per year.

Finally, it is planned by the Auger collaboration to build the northern part of the Pierre Auger Observatory. In 2005 the site was chosen in southeast Colorado, USA. It will consist of an array of 4000 SD stations deployed on an area of $20\,000\text{km}^2$, arranged at $\sqrt{2}$ miles array spacing on a square grid. The tanks will be observed by a set of 39 fluorescence tele-



Figure 6: Site map for the Auger North. FD and SD stations are represented, as well as the Distant Laser Facility (DLF). An infill array is predicted around S12 telescopes. Ref.: [7]

scopes arranged in five locations. Research and development works on a small SD array, atmospheric monitoring, electronics and communications systems have already started and the construction is planned nowadays to start in the year 2011. Assuming the same UHECRs flux in the north, Auger North and South together will detect approximately 180 trans-GZK events per year.

5. Conclusion

The Pierre Auger Observatory is the world's largest array dedicated to the detection of UHECRs. It combines two of the most important experimental techniques reducing systematic errors and providing model independent energy calibration. Scans have been done in the data for primaries anisotropies and no excess has been found in the galactic centre region. However a correlation with active galactic nuclei was reported. The flux of cosmic rays above 10^{18} eV has been measured with unprecedented precision showing a suppression above GZK cutoff energy. The highest energy

events show a trend towards heavier compositions. Plans for the expansions and the future construction of the northern site were reported in this paper.

The author thanks the colleagues from Auger collaboration for providing the material presented here. He expresses his special gratitude to Prof. Alex Gomes Dias (CCNH/UFABC, Brazil) for the invitation to speak on the 5th International School on Field Theory and Gravitation. He is also thankful to FAPESP, CNPq and CAPES for the financial support.

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