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Results from the Pierre Auger Observatory

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Abstract.

The Pierre Auger Observatory has been designed to investigate the origin and nature of Ultra High Energy Cosmic Rays. The combination of information from a surface array, measuring the lateral distributions of secondary particles at the ground, and fluorescence telescopes, observing the longitudinal profile, provides an enhanced reconstruction capability and opens the way for a multi-messenger approach. A review of selected results is presented, covering the measurement of energy spectrum, arrival directions, and chemical composition. Finally, the motivation and the status for the ongoing major upgrade of the Observatory, AugerPrime, will be discussed with the emphasis given to future perspectives.

1. Introduction

The Pierre Auger Observatory [1] is the largest cosmic ray Observatory in the world. It is located in the Province of Mendoza, Argentina, and consists of a surface array (SD) of about 3000 km² overlooked by 27 air fluorescence telescopes (FD) grouped in four sites, which together provide a powerful instrument for air shower reconstruction. The SD comprises 1600 water-Cherenkov detectors separated by 1500 m in a triangular grid, plus a smaller nested array of 61 additional detectors spaced by 750 m covering an area of 23.5 km². The FD measurements provide a nearly calorimetric estimate of the primary energy, almost independent of the assumptions on hadronic interaction models at the highest energies. The operation of the FD is however restricted to a duty cycle of about 15% [1] because it is limited by the atmospheric conditions while the SD measurements are made for about the 100% of the time. The hybrid paradigm relies on the fact that it is possible to calibrate the SD signal using the events simultaneously recorded by the FD, the so-called hybrid events, avoiding to a large extent the use of Monte Carlo simulations to reconstruct the energy. The hybrid technique allows us to achieve good control of the systematic uncertainties in the energy scale.

2. The energy spectrum

The energy spectrum is a key observable for the understanding of the origin and nature of ultra-high energy cosmic rays (UHECRs). An update of this measurement from 3×10^{17} eV up to 10^{20} eV at the Pierre Auger Observatory was presented in [2]. Four different data samples have been used to derive just as many independent measurements of the energy spectrum. Three data sets come from SD (the so-called vertical showers with zenith angle $\theta < 60^\circ$ recorded by SD-750 m and by SD-1500 m, the so-called horizontal events with zenith angle $60^\circ < \theta < 80^\circ$



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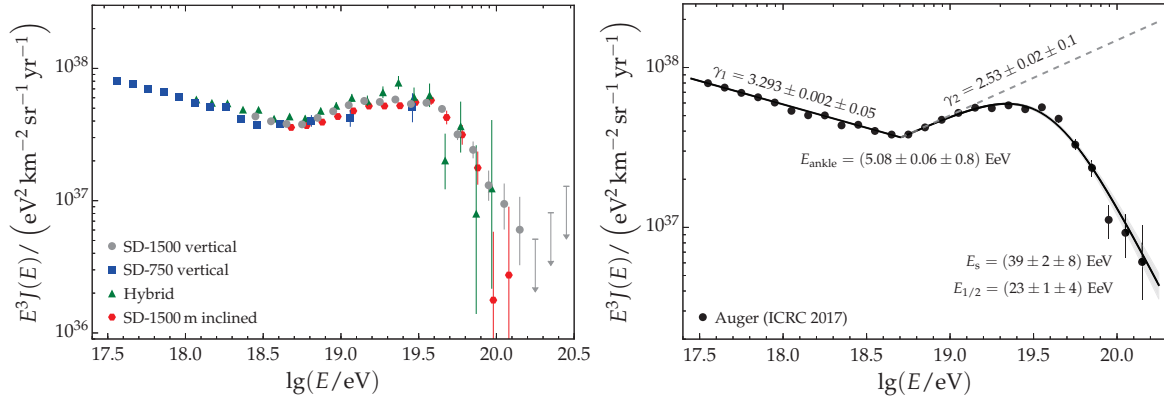


Figure 1. Left: The energy spectra obtained with SD 1500 vertical, inclined, hybrid and SD 750 events. The systematic uncertainty on the energy scale, common to all of them, is 14%. Right: The combined spectrum and the fitting function with the fitting parameters [2].

recorded by SD-1500) and one comes from FD (hybrid events with $\theta < 60^\circ$). The total exposure exceeds $67,000 \text{ km}^2 \text{ sr yr}$, and relies on the energy scale provided by the fluorescence detector. All spectra are shown together in Fig. 1, left. The four measurements agree within the systematic uncertainties, dominated by the one on the energy scale (14%). The systematic uncertainties on the flux are between 5 and 10%. A combined spectrum can be obtained by means of a maximum likelihood fit. The likelihood function is defined in such a way as to fit all the four data sets globally. The flux normalizations are used as additional constraints to obtain the flux scaling factors that match them: $(-0.8 \pm 0.2)\%$ for the SD 1500 vertical, $(-1 \pm 4)\%$ for the SD 750, $(5.4 \pm 0.7)\%$ for the SD 1500 horizontal and $(-6 \pm 2)\%$ for the hybrid. To obtain the spectral parameters, the combined spectrum is fitted with the function

$$J_{\text{unf}}(E) = \begin{cases} J_0 \left(\frac{E}{E_{\text{ankle}}} \right)^{-\gamma_1} & E \leq E_{\text{ankle}} \\ J_0 \left(\frac{E}{E_{\text{ankle}}} \right)^{-\gamma_2} \left[1 + \left(\frac{E_{\text{ankle}}}{E_s} \right)^{\Delta\gamma} \right] \left[1 + \left(\frac{E}{E_s} \right)^{\Delta\gamma} \right]^{-1} & E > E_{\text{ankle}} \end{cases} \quad (1)$$

The spectrum, the fit and the optimized parameters are plotted in Fig. 1, right. An ankle is found at $E_{\text{ankle}} = (5.08 \pm 0.06(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{18} \text{ eV}$, while the suppression is at $E_s = (3.9 \pm 0.2(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{19} \text{ eV}$. The energy $E_{1/2}$ at which the integral spectrum drops by a factor of two below what would be the expected with no steepening is $E_{1/2} = (2.26 \pm 0.08(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{19} \text{ eV}$. The spectral indices are: $\gamma_1 = 3.293 \pm 0.002(\text{stat.}) \pm 0.05(\text{syst.})$, $\gamma_2 = 2.53 \pm 0.02(\text{stat.}) \pm 0.1(\text{syst.})$ while $\Delta\gamma = 2.5 \pm 0.1(\text{stat.}) \pm 0.4(\text{syst.})$.

3. Mass composition

The knowledge of the composition of cosmic rays is a cornerstone for identifying a possible transition from galactic to extra-galactic sources and for the understanding of the nature of the energy-spectrum features. One of the most robust and precise observables to infer the composition from air-shower measurements is the atmospheric depth at which the shower reaches its maximum size, X_{max} . Experimentally, the longitudinal profile of the shower can be measured using the fluorescence light emitted by molecules of atmospheric nitrogen excited by EAS particles. At the Pierre Auger Observatory such measurements are performed using the fluorescence detector including the High Elevation Auger Telescopes (HEAT). The HEAT telescopes have expanded the field of view of the Coihueco FD site from $2^\circ \div 30^\circ$ up to $2^\circ \div 60^\circ$ in elevation, which allows one to observe nearby low energy showers ($E < 10^{17.8} \text{ eV}$). A shower

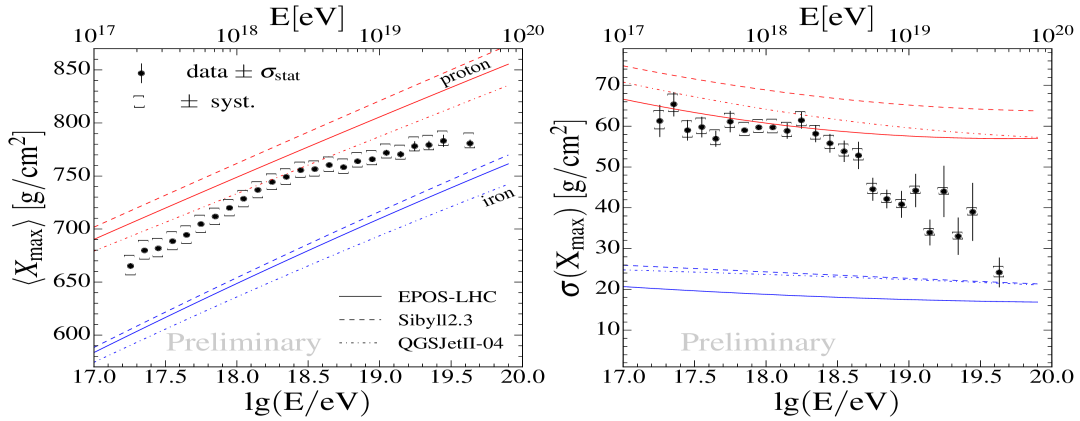


Figure 2. The mean (left) and the standard deviation (right) of the measured X_{max} distributions as a function of energy compared to air-shower simulations for proton and iron primaries.

is reconstructed accurately only if its X_{max} is within the telescope field of view. Shallow or deep events are more likely to have their X_{max} values outside it and have larger chances to be excluded from the analysis. A fiducial cut aimed at the rejection of events with biased reconstruction is then applied following the strategy described in detail in [3].

The latest measurements from the Pierre Auger Observatory are published in [4]. Between $10^{17.2}$ and $10^{18.33}$ eV the observed elongation rate, defined as the rate of change of $\langle X_{max} \rangle$, is $(80 \pm 1) \text{ gcm}^{-2}$ per decade (Fig. 2, left). This value, being larger than that expected for a constant mass composition ($\sim 60 \text{ gcm}^{-2}$ per decade), indicates that the mean primary mass is becoming lighter with increasing energy. At energies above $10^{18.32}$ eV the elongation rate becomes significantly smaller, $(26 \pm 2) \text{ gcm}^{-2}$ per decade, suggesting that the composition is becoming heavier with increasing energy. The fluctuations of X_{max} (Fig. 2, right) decrease above $10^{18.3}$ eV, and this also provides an indication that the composition is becoming heavier with increasing energy. The implication of the distributions of X_{max} have been studied in detail by the Pierre Auger Collaboration, by considering different assumptions on composition and on hadronic interaction models [5]. Regardless of what interaction model is assumed, Auger data are not well described by a mix of protons and iron nuclei over most of the energy range. Acceptable fits can be obtained when intermediate masses are included. A combined fit of both flux and composition of ultra-high energy cosmic rays has been performed for energies above 5×10^{18} eV [6]. A simple astrophysical model consisting of identical sources uniformly distributed in a comoving volume has been adopted. Proton, helium, nitrogen and iron nuclei are injected at the source assuming a power law spectrum and a rigidity dependent exponential cut-off. The spectrum is best fitted by a succession of cutoffs of the different group of elements thus indicating that the flux at Earth could be limited by the maximum rigidity reached at the source. Moreover, the best fit suggests a very hard source spectrum, with index ~ 1 , and an injection of mostly intermediate mass nuclei, with very few protons or iron nuclei.

4. Search for anisotropies

A powerful tool for the understanding of the origin of cosmic rays is the study of the distribution of their observed arrival directions. Anisotropies appearing on large angular scale can be caused by the propagation of cosmic rays and/or by their source distributions in the sky. The search for dipolar or multipolar structures is then complementary to spectrum and mass measurements. The observation, significant at a level of more than 5.2σ , of a large-scale anisotropy in arrival

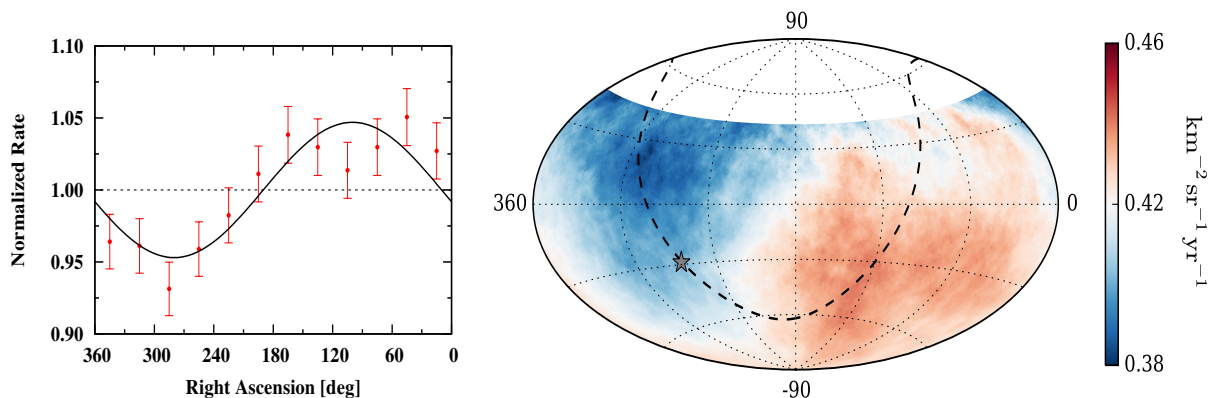


Figure 3. Left: Observed number of events, normalized to the mean, as a function of the right ascension, for $E \geq 8$ EeV. The black line is a sinusoidal function showing the first harmonic in right ascension. Right: Map of the flux of cosmic rays above 8 EeV in equatorial coordinates and smoothed with a 45° top-hat window. The star represents the direction of the Galactic center and the dashed line shows the Galactic plane.

directions of cosmic rays above 8 EeV ($1 \text{ EeV} = 10^{18} \text{ eV}$) was recently reported [7]. A standard approach to study the distribution at large angular scales is to perform a classical harmonic analysis generalized by introducing weights. The weights take into account possible small modulations in the coverage of the array arising from the variations in its operating size as a function of time and for the effects of a net tilt of the array surface. In Figure 3, left, the distribution of the normalized rate for 32187 events with $E \geq 8$ EeV is shown as a function of right ascension (integrated in declination). Error bars are 1σ uncertainties. The solid line shows the first harmonic modulation, which is in good agreement with the data ($\chi^2/n = 10.5/10$). In figure 3, right, the flux of cosmic rays with $E \geq 8$ EeV is shown, smoothed in angular windows of 45° to better visualize the dipolar pattern. The observed anisotropy above few EeV is indicative of an extragalactic origin. Several arguments support this conclusion [8], including the fact that the direction of the dipole determined above 8 EeV lies $\sim 125^\circ$ off the center of the Galaxy. Moreover, models proposing galactic sources up to the highest energies would require a predominantly heavy composition at EeV energies, which is in disagreement with observations (see Sec. 3).

Further studies at intermediate and small angular scale with *a posteriori* explorations have been performed and the results have been presented in [9]. The two largest departures from isotropy above 40 EeV, with significance of about $\sim 3\sigma$, are found around the direction towards Centaurus A and the most luminous AGNs of the *Swift*-BAT catalog [10].

A dedicated and completely new analysis [9] was performed in order to examine the correlation of our highest energy events with two nearby populations of extragalactic gamma rays sources, namely star-forming galaxies and AGNs motivated by the observations of the *Fermi*-LAT satellite. A 2.7σ excess has been found in the directions of the active galaxies, while with the starburst galaxies there is a 4σ deviation from isotropy at an intermediate angular scale of 13° .

5. Towards the upgrade

Our current understanding of UHECR has much improved along the past decade. Nevertheless a fully consistent interpretation of data on anisotropy, spectrum and mass composition is limited by the lack of knowledge at the highest energies. So far, we can hardly discriminate whether the energy spectrum is suppressed because cosmic rays are produced within a maximum rigidity scenario or because they undergo a photo-disintegration along their propagation [11]. We should

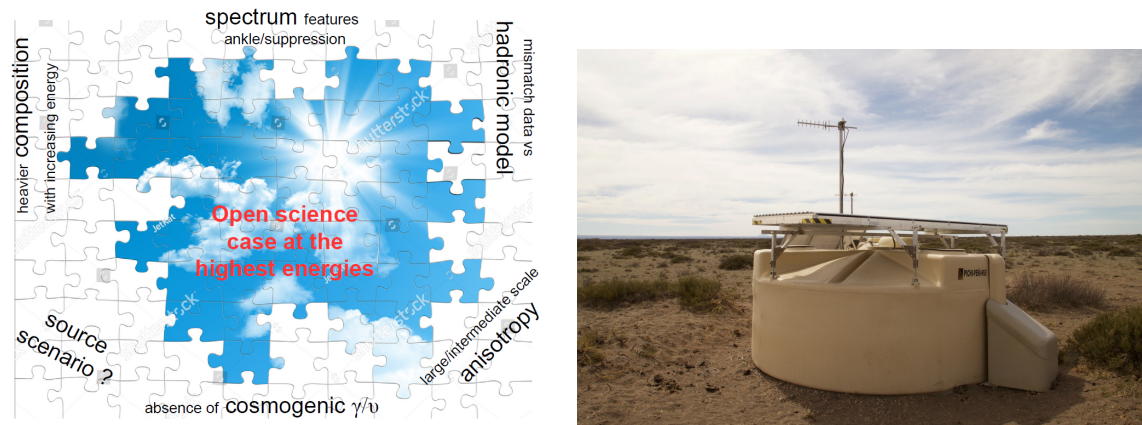


Figure 4. Left: Shedding light to the unsolved puzzle. Right: One station of the Auger upgrade Engineering Array, AugerPrime [13].

also understand how to reconcile measurements with predictions from hadronic interaction models as they lead to a sizeable discrepancy with observation concerning the muon component of the showers [12]. A sketch of this intriguing puzzle is shown in Fig. 4, left.

In order to extend the composition sensitivity of the Auger Observatory into the flux suppression region, an upgrade of the Auger Observatory, AugerPrime, has been planned [13]. Its main goal is to provide, on a shower-by-shower basis, additional measurements of mass composition sensitive observables, allowing an estimation of the primary mass of the highest energy cosmic rays. The study of the origin of the flux suppression will provide fundamental constraints on the astrophysical sources and will allow us to derive more precise estimates of gamma-ray and neutrino fluxes at ultra-high energy. AugerPrime aims at reaching a sensitivity as small as 10% in the measurement of the flux contribution of protons in the suppression region.

The first twelve stations of AugerPrime (one fully equipped station is shown in Fig. 4 right), forming the Engineering Array of the upgrade, were assembled in Europe and deployed at the Pierre Auger Observatory in September 2016. The stations of the Engineering Array (EA) are partially located inside the standard array (9 detectors) and partially in the smaller nested array (3 detectors) [14]. The EA has been in continuous data-taking mode since the beginning of October 2016 and has collected more than 30000 local triggers. Standard stations in the EA area have been used to reconstruct more than 3000 events.

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