Reviewing recent results from Pierre Auger Observatory

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Abstract. We present some results from the last three years of operation of the Pierre Auger Observatory. This is a short version of the review talk presented at the 18th International Symposium on Particles, Strings and Cosmology (PASCOS2012). The main topics are related to ultra-high energy cosmic rays and their interactions: energy spectrum, mass composition, neutrino astrophysics and very high energy hadronic interactions.

1. Open questions in cosmic ray physics at energies above $10^{18}$ eV

A bulk of questions that were traditionally set for different cosmic-ray experiments operating below $10^{18}$ eV can nowadays be addressed by the Pierre Auger Observatory, due to its capability of investigating different aspects of air showers. The questions are about the topics: sources of cosmic rays at such energies, the acceleration processes taking place, the propagation along astronomical distances, the large-scale structure of the universe and the intervening magnetic fields and the mass composition. Another relevant question is: can we contribute to the knowledge of particle interactions at these otherwise inaccessible energies, of the order 450 TeV in the center-of-mass system? We will report here topics like energy spectrum, mass composition, neutrino astrophysics and very high energy hadronic interactions.

2. The Pierre Auger Observatory

The Auger Observatory is an experimental complex that was designed to detect cosmic rays with energies above $10^{18}$ eV. It is situated near Malargüe, in the Province of Mendoza, Argentina at 35.1° - 35.5° S, 69.0° - 69.6° W and 1400 m asl. Its location gives a special view of the galactic center. The proposal of the Observatory aims to observe in details the development of air showers in the atmosphere, by calorimetric methods and also to observe the air shower front when it reaches ground-based detectors [1]. This is an important capability of Auger Observatory: because the design includes the use of fluorescence and ground array techniques, it is a hybrid experiment. The original design was completed in 2008, and since then many improvements have been made both to the setup and also to the analysis procedures. As a consequence, a broad view of the properties of very high energy air showers - their components and their time structure can be addressed and thus the main aspects of the primary cosmic rays can be inferred.

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3. Air shower features in the atmosphere and in ground-based modules as seen by the Auger Observatory

The fluorescence and surface detector techniques are combined, in the Observatory, to give detailed information about air showers. The experiment spans over an area of 3000 km$^2$ in the desertic region of Malargüe, and its aperture is about 7000 km$^2$ sr. Its Fluorescence Detector (FD) is an ensemble of 27 optical telescopes, grouped in 5 buildings, that can observe the longitudinal development of the shower in the atmosphere in a stereoscopic view. The shower profile is derived by detecting the fluorescence light emitted by excited nitrogen molecules - this is an established technique, used in previous experiments as Fly’s Eye [2] and HiRes [3] and now in Telescope Array [4]. In the Auger Observatory, the telescopes record light profiles from showers that may be some tenths of kilometers away, over the ground array. This light suffers attenuation along the path from the production point to the telescopes, thus the detected profile must be corrected to reproduce the fluorescence production at the origin. To estimate the attenuation, which is due to molecules, aerosols and clouds, regular measurements of the atmospheric conditions are performed: UV laser shooting, radiosonde launching, optical observations and cloud measurements. They are incorporated into the event reconstruction software, so that the reconstructed fluorescence profile gives an almost calorimetric measurement of the energy of the primary particle. A typical shower profile, obtained with two telescopes, can be seen in figure 1. The duty cycle of the Fluorescence Detector is 10 - 15 %.

![Figure 1](image1.png)  
**Figure 1.** A typical longitudinal profile (energy deposit X depth), as seen by fluorescence telescopes. Putting together information from longitudinal and lateral (see figure at right) profiles in a event-to-event basis, a universal calibration curve is constructed.

![Figure 2](image2.png)  
**Figure 2.** A typical lateral profile, as seen by the ground array (SD). VEM is the “vertical muon equivalent”, the signal generated by a vertical muon at the center of the module. The signal at 1000 m from shower core is a convenient parameter to estimate shower energy.

The ground array, named Surface Detector (SD), consists of 1660 stations - water-Cherenkov tanks and their associated electronics arranged in triangular cells, where each station is 1.5 km apart from another. The Cherenkov light generated in water is collected by 3 photomultipliers and the signal is read out by 40 MHz FADC’s, which give a 25 ns time scale for further shower reconstruction. The signal unit is called Vertical Muon Equivalent (VEM), the signal generated by a muon crossing the water tank vertically, at its center (figure 2). This unit is very suitable to continuously calibrating particle signals, accounting for different conditions of operation. The Surface Detector has a duty cycle near to 100%.
Figure 3. A high precision spectrum, obtained by combination of hybrid technique and SD technique. The calibration uses high-quality hybrid events, so that both inputs to this figure have the same systematic uncertainty in the energy scale. Three power laws and a smooth curve (solid) are fitted to the data. The features of this energy region are important to elucidate the well known GZK-cut quest [14].

4. Event Reconstruction
An important piece in the event reconstruction is the lateral distribution of the signal, as recorded in the Cherenkov stations. A lateral distribution function, based on shower simulations and previous data from the Auger Observatory, is fitted to the experimental curve, in order to obtain the value of signal at 1000 m from shower core (see figure 2). A universal calibration curve using this information and those from fluorescence detector, is used to obtain the primary energy, within a systematic error of 22%, whereas the statistical error is \( \sim 15 \% \). The calibration curve is then used for all showers, also for non-hybrid detection. Figure 3 shows a high-precision energy spectrum, at energies above \( 10^{18} \) eV.

The operation in hybrid mode optimizes event reconstruction: the timing information from telescope pixels together with the time and signal structure from surface stations, as cited above, gives a resolution for core location within 50 m and an angular resolution for the arrival direction of primary of 0.6° [8]. Non hybrid events have angular resolution about 1.5°.

5. Mass Composition
The atmospheric profile of an extensive air shower, i.e, the number of particles as a function of depth, carries important information about the mechanisms of particle production and absorption. The depth at which the shower reaches its maximum, called \( X_{\text{max}} \) in the literature gives important clue about the mass of the primary particle [6]. The change of \( <X_{\text{max}}>_\beta \) per decade of energy, the so-called Elongation Rate and its shower-to-shower fluctuations, RMS \( (X_{\text{max}}) \) are sensitive to changes in mass composition with energy. These variables have different behaviors, if the primary is a proton or an iron nucleus, as predicted by different hadronic interaction models. Figure 5 shows the experimental behavior of both variables with energy, together with the predictions of the models EPOS 1.99, SIBYLL 2.1, QGSJET01C, QGSJETII [6]. We find a tendency in the composition: if the models describe correctly the interactions, when the energy gets higher, the composition departs from that expected for protons and tends
to that expected for iron primary.

![Graph](image)

**Figure 4.** Behavior of $<X_{max}>$ and RMS ($X_{max}$) as function of primary energy and the prediction of hadronic models in the versions that are more compatible with recent experimental data: EPOS 1.99, SIBYLL 2.1, QGSJET01C, QGSJETII [6]. The numbers in each energy bin are attached to the experimental points.

6. Neutrinos

It is expected that protons with energies $10^{20} - 10^{21}$ eV would, in their interactions, produce neutrinos above the threshold of EeV telescopes [11]. Particle production scenarios like those of “top-down” and “bottom-up” [12, 13] predict very-high energy neutrinos, that could be detected by existing neutrino telescopes. The surface array of Pierre Auger Observatory can detect air showers with zenith angles from zero to 90$^\circ$ and even larger than this value - this is the case when a neutrino interacts with Earth’s crust and generates a shower. Among the air showers, those almost horizontal, with zenith angles near 90$^\circ$ could be candidates to neutrino-initiated events, under some assumptions, that will not be discussed here. The primary neutrinos, in this case, are called down-going neutrinos, whereas those Earth-skimming are called up-going neutrinos. We can put limits at 90 percent CL per half decade of energy, for down-going (all flavours) and up-going neutrinos and compare them with other experimental results, as shown in fig 6. No candidate of neutrino induced showers were found so far, allowing us to set upper limits to their flux. Further details about neutrino initiated showers registered in Pierre Auger Observatory can be seen in ref. [15, 16].

7. Hadronic Interactions

Although cosmic ray experiments are, in general, not designed to identify single particles, like accelerators, some quantities that are measured in extensive air showers are sensitive to the non perturbative and semi-hard processes of QCD: inelastic cross-sections, multiplicities of muonic and electromagnetic components, their density per rapidity interval and others [17, 18]. The fluorescence telescopes, as they are mounted in Auger Observatory, supply enough information about the rise and fall of particle number (or energy deposited) in the atmosphere to estimate the inelastic proton-air cross section. This cross section, obtained from $E_{lab} = 10^{18} - 10^{18.4}$ eV showers, corresponding to about $\sqrt{s} = 57$ TeV, detected in the Auger Observatory, together with other measurements and predictions from hadronic models, is shown in figure 7. From this cross section, we can calculate, using Glauber Theory, the proton-proton cross section, that can be seen in reference [7].
Figure 5. Ninety-percent Confidence Level limits for diffuse flux of down-going ($\nu$) and Earth-skimming ($\nu_\tau$) neutrinos from a selected set of events as given by Pierre Auger Observatory, compared to limits from other experiments. See ref. [15] for further details.

Figure 6. Inelastic proton-air cross section at $\sqrt{s} = 57$ TeV, obtained from shower longitudinal profile in Auger Observatory, together with other measurements. The predictions of hadronic models to the cross section are also shown [7].

The multiplicity of muons in a air shower is related to the type of primary particle and can also give indications of changes in the hadronic processes themselves. The Auger Collaboration has reported the observation of muon multiplicity in air showers that exceed the values predicted by hadronic interaction models [19, 20].
8. Conclusions

After the completion of the Observatory in 2008, several enhancements to the original project were added, aiming to better characterize air showers. They involve radio detection, molecular Bremsstrahlung detection, improvements in muon detection, enhancements in atmospheric monitoring, improvements in analysis procedures and others. With these enhancements, the energy spectrum will be studied with a $10^{17}$ eV threshold in primary energy.

The Pierre Auger Observatory has contributions to cosmic ray physics in the aspects concerning energy spectrum, photon and neutrino fluxes, hadronic interactions and others. We should stress the precision of the measurements - it is remarkable, compared to the precision of other experiments at these extremely high energies. Other outstanding features of the Observatory are, already, the large event library and also the implementation of new methods in data analysis.

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