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From The Pierre Auger Observatory to AugerPrime

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Abstract. In the present work we report the principal motivation and reasons for the new stage of the Pierre Auger Observatory, AugerPrime. This upgrade has as its principal goal to clarify the origin of the highest energy cosmic rays through improvement in studies of the mass composition. To accomplished this goal, AugerPrime will use air shower universality, which states that extensive air showers can be completely described by three parameters: the primary energy E_0, the atmospheric shower depth of maximum $X_{\max}$, and the number of muons, N_μ. The Auger Collaboration has planned to complement its surface array (SD), based on water-Cherenkov detectors (WCD) with scintillator detectors, calls SSD (Scintillator Surface Detector). These will be placed at the top of each WCD station. The SSD will allow a shower to shower analysis, instead of the statistical analysis that the Observatory has previously done, to determine the mass composition of the primary particle by the electromagnetic to muonic ratio.

1. Introduction

The origin of the ultra-high energy cosmic rays (UHECR) is still an open science case. The UHECR offer information about the most powerful astrophysical sources and they allow one to investigate particle acceleration at the highest energies, in a range that can not be covered by the particle accelerators. The mass composition of ultra-high energy cosmic rays is a very important observable to understand their origin. The atmospheric depth at which the shower reaches its maximum size, $X_{\max}$, is one of the most robust variables to infer the mass composition of air showers.

The Pierre Auger Observatory uses fluorescence detectors to measure the $X_{\max}$ and operates with an enhancement, the High Elevation Auger Telescopes (HEAT), which allows Auger to go down in energy to 10^{17} eV, the range of study covers from 10^{17} to $> 10^{19}$ eV.

With three decades of data, the Pierre Auger Observatory has some interesting results about $X_{\max}$. Between 10^{17} and $10^{18.3}$ eV, $X_{\max}$ increases by around 85 g cm^{-2} per decade of energy, Fig. 1. This value is larger than the one expected for a constant mass composition ($\sim$ 60 g cm^{-2}/decade) and indicates that the mean primary mass is getting lighter. Around $\approx 10^{18.3}$ eV the observed rate of change of $\langle X_{\max}\rangle$ becomes significantly smaller ($\sim$ 26 g cm^{-2}/decade) indicating that the composition is becoming heavier. The first two moments of the $X_{\max}$ distribution ($\langle X_{\max}\rangle$ and $\sigma(X_{\max})$) are related to the first two moments of the distribution of the logarithm of masses of primary particles ($\langle \mathrm{lnA}\rangle$ and $\sigma^2(\mathrm{lnA})$) as shown in [1]. The lowest values

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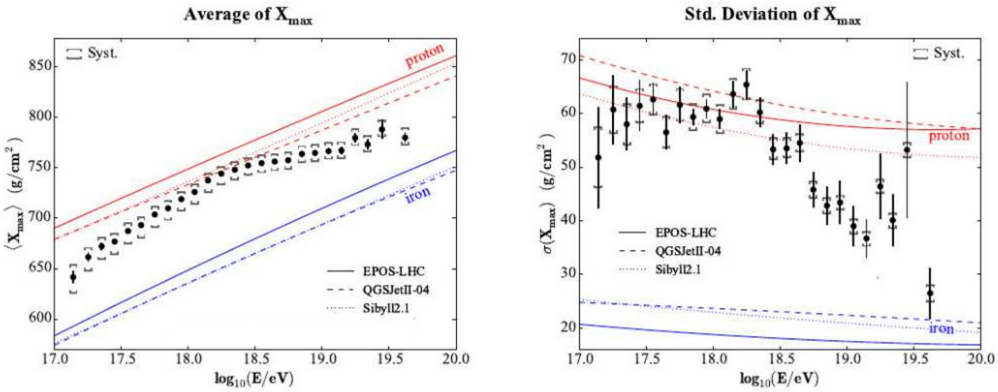

Figure 1. In the left plot the mean of the measured $X_{\max}$ distribution is shown. In the right plot is the standard deviation of the $X_{\max}$ distribution. In both cases the $X_{\max}$ as a function of energy is compared to air-shower simulations for proton and iron.

for the primary mass are at around an energy of $10^{18.3}$ eV, and increase for higher energies. The change might be an indication that the relative fraction of protons becomes smaller for energies above $\approx 10^{18.3}$ eV (see [2]). 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 [2]. Despite use of the interaction models, the Auger data are not well described by a mix of protons and iron nuclei over most of the energy range. The best fits are obtained by considering intermediate masses for the mass composition.

2. Air Shower Universality

Air shower universality says that extensive air showers (EAS) can be completely characterized by three parameters: the primary energy E_0, the atmospheric depth of shower maximum $X_{\max}$, and the number of muons, N_μ. From these parameters, the $X_{\max}$ and the N_μ depend of the mass of the primary particle, and are subject to significant shower to shower fluctuations. It is possible to place constraints on hadronic interaction models, once these two parameters are measured and compared with simulations. In some previous studies it has been proved that the energy spectra and the angular distributions of electromagnetic particles [3], as well as the lateral distribution of energy close to the shower core, are universal [4] [5], i.e. they are functions of E_0, N_μ and the atmospheric depth $X_{\max}$ only.

Another important fact we should consider is that some aspects of Auger SD data are not completely understood, such as: the attenuation curve,the difference between the spectrum obtained from inclined events (which are events with zenith angle between 60° and 80°) in comparison with the spectrum obtained from data with zenith angles less than 60°, when they are shown as a fractional difference (also called the residual) [6]. Also, the information of the FADC traces from the water-Cherenkov stations (belonging to the SD) located far from shower cores have been used to make a reconstruction of the muon production depth, however the current level of systematic uncertainties associated with its determination prevent us from using this to make conclusive statements on mass composition [7].

All the approaches presented so far determine the muon normalization indirectly, leaving it convoluted with the effects of shower development and fluctuations, or relying on the energy scale given by the fluorescence data.

3. Observables

In this work we present the universality in the interpretation of surface detector data. We need to separate the properties of the showers, including the electromagnetic component, the average depth of shower maximum $\langle X_{\max}\rangle$, the normalization of the muon signal at 1000 m (N_μ) and the surface detector energy scale [8]. The normalization of the muon signal is directly related to the number of muons in the shower. The $\langle X_{\max}\rangle$ has been measured by the fluorescence detector with very well known uncertainties. We used this knowledge to infer the number of muons as function of energy in the same way as the energy scale from surface detectors.

The ultra-high energy cosmic rays are very difficult to measure because they have a low rate. For this reason, the Observatory covers a large area, with large separation between detectors. In this way, the shower properties are measured from different points at different distances from the shower core. When the size of the shower is reconstructed, the lateral distribution function (LDF), which describes the fall-off of signal size with the distance from the shower core, leads to a related a uncertainty in both the location of the shower core and in the measurement of the integrated LDF. To avoid the large measurements fluctuations, Hillas proposed a method using the signal at some distance (r_{opt}) from the shower core to classify the size of the shower, and ultimately the energy of the primary particle [9]. The advantages of this method are: (*i*) the effect of uncertainties in the LDF are minimized at a particular core distance, and (*ii*) although the total number of particles at ground level is subject to large fluctuations, the fluctuations of the particle density at the chosen distance from the core are quite small. For example it was shown that at 10^{17} eV the RMS variation in the total number of particles is $\approx 67\%$; for the same shower the RMS variation in the signal of a water-Cherenkov detector at 950 m is $\approx 6\%$. His conclusion was shown to be robust for a variety of hadronic propagation models and energies.

To measure the energy of the primary particle two steps are necessary. First, the detector signal must be measured at some distance from the core and, second, this characteristic signal must be linked to the energy of the primary particle. The Pierre Auger Observatory as a hybrid detector has the advantage of having a fluorescence detector which measures around 10% of the EASs observed with the surface array. The calorimetric energy measurement from the fluorescence detectors can be used to calibrate the characteristic signal from the surface detector. Identifying the optimum core distance r_{opt} for arrays with large spacing is problematic. Identifying the r_{opt} at which to measure the signal of an air shower, will minimize the uncertainty in the energy of the primary particle which follows from a lack of the knowledge of the true LDF. For the Pierre Auger Observatory the r_{opt} is 1000 m, so the characteristic signal will be $S(1000)$ and will be used to determine the energy of the primary particle. Around 1000 m the expected signal is robust against inaccuracies in the assumed LDF, better that 5% [10].

4. Electromagnetic and Muonic Component

In an extensive air shower the electromagnetic component (EM) is initiated by neutral pions, the EM component reaches its atmospheric depth of maximum directly related to the primary mass. The EM component shows universality features that have been used to study the Cherenkov light production in EAS [11] and is a very good estimator of the primary energy.

On other hand, the muon component is due to the charged pions; its maximum is about 100 g cm^{-2} deeper in the atmosphere. The muons bring information on the primary particle mass and the hadronic interaction models. The study of the well known "muon deficit" in simulations [12] as compared to data is mandatory in order to use the muons as composition observables. Also the study of muons can reduce the systematics in the energy scale.

Separating these two components with the Surface Auger for the Pierre Auger Observatory, can be very difficult:

- vertical muons deposit on average 240 MeV in the surface station, the signal being proportional to the station volume, their flux is from 1 to 3 orders of magnitude lower than the EM one.

- the EM component is made up of $\gamma's$ and, roughly one order of magnitude less, by $e^{\pm}$. The surface station acts in this case as a total absorption calorimeter. The average deposited energy per particle is $5 - 10$ MeV.

The temporal profile of the shower can be studied with great detail in each SD station, because their electronics digitizes the signals with a sampling rate of 40 MHz (in AugerPrime will increase to 120 MHz). Thanks to this characteristic it is possible to develop some techniques to separate the signal components [13]. Some of them are: the deconvolution of peaks in traces, the study of jumps and subsequent developments, the smoothing, or methods where the information about muons comes from universality properties of showers [8] [14].

In the current model adopted by the Observatory, shower universality has been tested in terms of the shower plane signal, i.e. there were only considered the shower particles passing through the top of a detector placed perpendicular to the shower axis. This avoids zenith angle dependencies [8]. The study was performed using simulations, the shower plane signals were divided into electromagnetic particles and muons. In order to have a better separation of the two components, there was included the signal from the electromagnetic decay products of muons in the muon component, leaving a "pure" electromagnetic component (S_{em} in VEM). It is important to mentioned that the electromagnetic decay products of muons contributes with 15% of the muon signal in the detector.

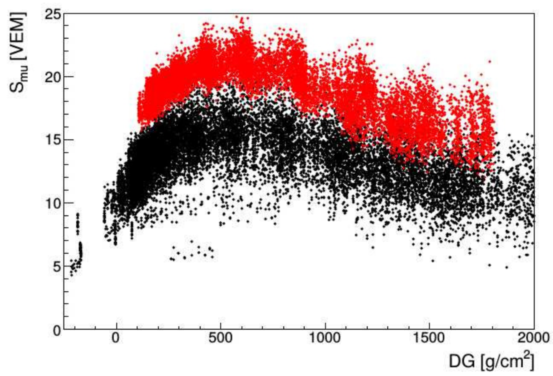

Figure 2. Simulated muon signals, in black for proton and in red for iron. The showers were simulated using QGSJetII/Fluka, between 0° and 70°.

In the Fig. 2, is shown the muon signal (S_μ) as function of DG $= X_{\text{ground}} - X_{\text{max}}$, which is the distance from the shower maximum to the detector along the shower axis (in g/cm^2). The proposed method has shown that the muon and electromagnetic components at 1000 m are completely determine by DG, and the overall muon normalization, N_μ. The parameter DG depends of X_{max} and θ, and it is possible to do a parametrization of $S_{1000} = S_{1000}(X_{\text{max}}, N_\mu, \theta)$ for a given energy.

5. AugerPrime

AugerPrime will be able to measure the different abundances of muons, photons and electrons in air showers at the surface ground level, to obtain a more precise handle on the primary cosmic ray composition, with increased statistics at the highest energies. The key to differentiating the ground-level air shower particles lies in improving the detection capabilities of the surface array.

AugerPrime consists in covering each of the 1660 water-Cherenkov surface station with planes of plastic-scintillator detectors (SSD) of area 4 m^2. This enhancement will allow the Auger

Observatory to determine the electron/photon versus muon abundances of air showers. The scintillator detectors will be housed in weatherproof enclosures, attached to the existing water-Cherenkov stations, as shown in Fig. 3. The scintillator light will be read out with wavelength-shifting fibers, which are bundled and attached to photomultiplier tubes Fig. 4. Since the surface stations are always working, the AugerPrime upgrade will acquire information for the full data set collected in the future [15].

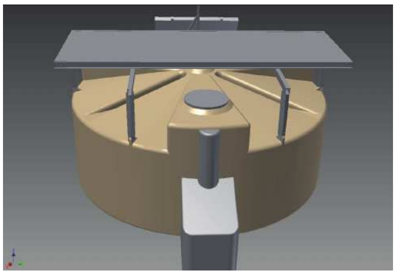

Figure 3. Drawing of SD station with scintillator detector (SSD) of area 4 m^2, housed in a weatherproof enclosure.

Figure 4. SSD detector with green wavelength-shifting fibers, which carry light to a photomultiplier tube(not shown).

The AugerPrime project includes other detector improvements. The dynamic range of the surface stations will be extended with the addition of a fourth photomultiplier. New electronics will be included, with faster sampling of the PMTs signals to a better identifications of the muon signals. New GPS will be implemented in each surface station to improve the timing accuracy and calibration. Also, some tests have been done with the fluorescence telescopes to extend measurements during nights with highly illuminated moon above the horizon. This will extend the duty cycle of the surface and fluorescence detector arrays of the Pierre Auger Observatory to 30% approximately. As a consequence, AugerPrime will have more precise measurements of the energy and $X_{\rm max}$ and therefore a better determination of the mass composition of the primary cosmic rays radiation.

In November 2015, the Auger Collaboration officially announced AugerPrime in Malargüe, Argentina, during a meeting with its International Finance Board and dignitaries from different collaborating countries. A renewed agreement was signed and it was establish that AugerPrime will be operate for 10 years. It is expected that, by 2018, the installation of the new detectors will be complete, in the meantime the Observatory will continue taking data.

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