PROCEEDINGS OF SCIENCE

# The Pierre Auger Observatory Upgrade

**Daniele Martello**[*a] **for the Pierre Auger Collaboration** [b]

[a]*University of Salento and INFN Lecce, via per Arnesano, 73100 Lecce, Italy*
[b]*Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina*
*E-mail:* auger_spokespersons@fnal.gov
*Full author list:* http://www.auger.org/archive/authors_icrc_2017.html

Over the past decade the Pierre Auger Observatory has accumulated the largest exposure to ultra-high energy cosmic rays, and provided a data set of unprecedented quality. The analysis of these data has led to major breakthroughs in the understanding of the origin and properties of the highest-energy cosmic rays, but a coherent interpretation has not yet been achieved. New questions have emerged, including that of the mass composition of cosmic rays in the energy region of the flux suppression, which is of key importance for making progress.

To answer these open questions, the Observatory has started a major upgrade, called AugerPrime. The upgrade program will include new plastic scintillator detectors on top of the water-Cherenkov detectors of the surface array (SD), more powerful SD electronics and an extension of the dynamic range with an additional PMT installed in the water-Cherenkov detectors. The main goal of AugerPrime is to improve the mass composition sensitivity of the surface detectors. At the end of 2016 an Engineering Array of the upgraded detectors was installed and it has taken data since then.

After reviewing the physics motivation of AugerPrime, an overview of the different parts of the upgrade will be given. The expected performance and the improved physics sensitivity of the upgraded Observatory will be discussed together with the first data collected with the Engineering Array.

*35th International Cosmic Ray Conference — ICRC2017*
*10–20 July, 2017*
*Bexco, Busan, Korea*

[*] Speaker.

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## 1. Introduction

The nature of ultra-high energy cosmic rays (UHECRs) above $10^{17}$ eV is still unknown, even if data collected in the last decade have partially answered these puzzling questions. Understanding the sources and the propagation properties of UHECRs is one of the key questions in astroparticle physics. The data collected with the Pierre Auger Observatory [1] have contributed to a number of steps forward in this field. The measurements confirmed with high precision the suppression of the primary cosmic ray energy spectrum, the differential flux falls to one-half of the value of the power-law extrapolation at energies above $4 \times 10^{19}$ eV [2]. This suppression is compatible with the Greisen-Zatsepin-Kuzmin (GZK) effect, but the level of its contribution to the cut-off remains unclear. The measured limits on the flux of photons [3, 4, 5] and neutrinos [6, 7] at ultrahigh energy indicate that top-down mechanisms such as the decay of super-heavy particles cannot be the main producer of the observed particle flux. The distributions of the depth of shower maximum ($X_{\mathrm{max}}$) have been used to determine the UHECR composition on Earth, indicating the presence of a large fraction of protons in the energy range of the spectral ankle. At the same time, according to the Auger data [8], the anisotropy of the arrival directions of these protons cannot be larger than a few percent. Moreover the proton component disappears at $10^{19}$ eV [9, 10] where heavier components appear.

The isotropy in the flux of the more energetic cosmic rays observed in numerous tests of the small-scale angular distribution is remarkable [11], challenging the original expectations that assumed only a few cosmic ray sources with a light composition at the highest energies. On the other hand, an evident dipole behavior is observed for energies above 8 EeV [12].

The all particle spectrum by itself and the knowledge of the composition below the suppression region cannot provide sufficient discrimination between the different astrophysical hypotheses, therefore the determination of the primary composition at energies higher than a few times $10^{19}$ eV is mandatory to reach any reliable conclusion. To explore these energies the Auger fluorescence detector is not adequate due to its limited duty cycle (presently 15%).

## 2. The motivation for AugerPrime

In order to extend the composition sensitivity of the Auger Observatory into the flux suppression region, an upgrade of the Auger Observatory (named AugerPrime[13, 14] ) has been planned. The main aim of AugerPrime 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 determine more precise estimates of gamma-ray and neutrino fluxes at ultra-high energy. The measurement of the flux contribution of the light elements will elucidate the physics potential of existing and future cosmic ray, neutrino, and gamma-ray detectors. Therefore, the aim of AugerPrime is to reach a sensitivity as small as 10% in the flux contribution of protons in the suppression region on a shower-by-shower basis.

The determination of the primary mass composition of ultra-high energy cosmic rays is deeply related to our understanding of extensive air showers and hadronic interactions. In the Auger data,



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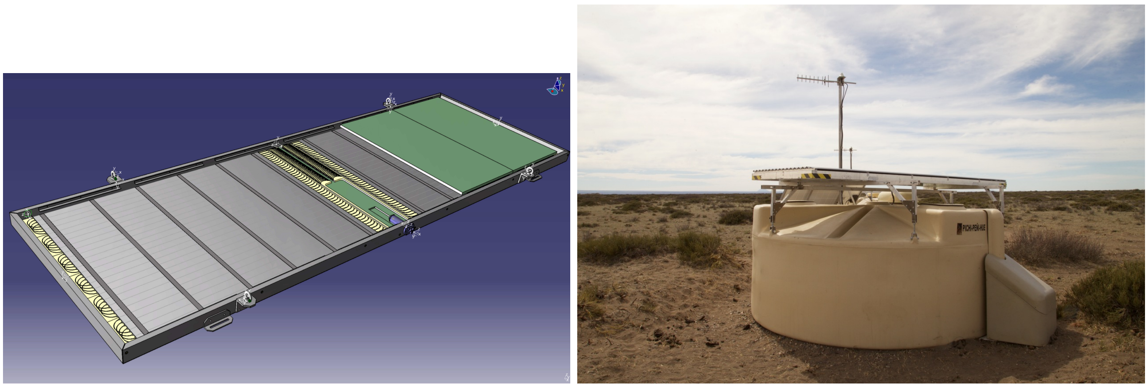

**Figure 1:** Left: the layout of the Surface Scintillator Detector (SSD); Right: One station of the AugerPrime Engineering Array.

there is a disagreement between the observed and expected muon numbers [15, 16], therefore it is of fundamental importance to study the hadronic multiparticle production in extensive air showers.

## 3. Description of AugerPrime

The AugerPrime upgrade consists of many improvements of the Pierre Auger Observatory. The most important is the installation of a new detector above each of the existing water-Cherenkov detectors (WCD). This new detector, named the Surface Scintillator Detector (SSD), consists of a plane of plastic scintillator that will be triggered by the larger WCD below it.

An SSD unit is a box of area 3.8 m $\times$ 1.3 m, containing two scintillator sub-modules, each composed of 24 bars of extruded scintillator produced at the Fermi National Accelerator Laboratory of about 1.6 m length, 5 cm width and 1 cm thickness [17]. The 3.8 m$^2$ scintillator planes are protected by light-tight, weatherproof enclosures, and mounted on top of the existing WCD with a strong support frame (see figure 1). The scintillator light will be collected with wavelength-shifting fibers inserted into straight extruded holes in the scintillator planes. The fibers (Kuraray Y11(300)M S-type) are bundled and connected from both sides to one 1.5" photomultiplier tube (PMT). The PMT selected in the baseline design is the model Hamamatsu R9420. It has a bi-alkali photo-cathode and a quantum efficiency of about 18% at the wavelength of 500 nm. This PMT has been chosen for its excellent linear response.

The other important improvement included in the AugerPrime program is the upgrade of the electronics of the SD and the extension of the dynamic range of the WCD. The new electronics will process both WCD and SSD signals [18]. It will increase the data quality thanks to better timing accuracy and a faster ADC sampling. The signals of the SSD and WCD will be sampled synchronously at a rate of 120 MHz (three times the current rate). The new GPS receiver will allow a timing accuracy of 5 nanoseconds, about a factor two better than the current value. Faster data processing and more sophisticated local triggers are enabled by the use of a more powerful processor and FPGA, and improved calibration and monitoring capabilities are foreseen. The dynamic range of the WCD will be enhanced by a factor 32 with an additional small (1") PMT that will be inserted in the WCD [19].

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To verify and fine-tune the methods used to extract shower muon content using the SSD and WCD stations, an underground muon detector (AMIGA) will be installed to provide a direct measurement of the muon content of a sample of showers observed by the upgraded Auger SD [20]. The AMIGA detector consists of 61 units deployed on a 750 m grid, instrumenting a total area of 23.5 km$^2$. Each units consists of a plane of plastic scintillator of about 30 m$^2$ that will be buried about 2.3 meters underground.

The Auger Fluorescence Detector (FD) [1] provides information about extensive air showers such as a model-independent energy reconstruction and longitudinal development profiles of the extensive air showers. The main limitation of the FD is its duty cycle, currently at the level of 15%. A significant increase of the duty cycle is possible by the extension of the FD operation to times at which a large fraction of the moon in the sky is illuminated. During such operating conditions the PMT gains must be reduced by lowering the supplied high voltage to avoid high anode current and, therefore, a deterioration of the PMTs. The HV power supplies used for the FD allows switching between two high voltage levels and the PMTs can be operated at the nominal gain (standard operation mode) and a lower gain (new operation mode for periods of high night sky background).

## 4. Expected Performance

A thin scintillation detector, which is mounted above the larger WCD, provides a robust and well-understood scheme for particle detection that is sufficiently complementary to the water-Cherenkov technique and permits a good measurement of the density of muons. This can be understood by comparing the signal contributions for different shower components as shown in figure 2. Over a wide range in lateral distance, the ratio between the integrated signal of electromagnetic particles (photons and electrons) and that of muons is more than a factor two higher in an unshielded scintillation detector compared with a water-Cherenkov detector [13].

One of the key aims of the Pierre Auger upgrade is to discriminate between different compositions and physics scenarios in the energy range of the flux suppression. This is very difficult to demonstrate without knowing what composition to expect. For this reason two benchmark descriptions have been chosen as representations of a maximum-rigidity scenario (scenario 1 corresponding to the best fit solution in [22]) and of a photo-disintegration scenario (scenario 2 corresponding to the second minimum in [22]). While the two scenarios approximately reproduce the spectrum and the $X_{\rm max}$ and $\sigma(X_{\rm max})$ so far measured by the Pierre Auger Observatory, they are generated by very different compositions and spectra at the sources.

Figure 3 shows the mean $X_{\rm max}$ and the corresponding $\sigma(X_{max})$ for these scenarios, using the SD data of the upgraded observatory. The $\sigma(X_{\rm max})$ contains the intrinsic air-shower fluctuations and the detector resolution. The same quantities expected for pure proton and pure iron compositions are illustrated. While the mean $X_{\rm max}$ and $\sigma(X_{\rm max})$ are very similar up to $10^{19.2}$ eV, which corresponds to the energy range presently covered by data of the fluorescence telescopes, the models predict significantly different extrapolations into the suppression region and the two scenarios can be distinguished with high significance and statistics. In addition to these studies, the availability of muon information on an event-by-event basis allows studies of the features of hadronic interactions. Moreover, the information on a event-by event basis will permit the selection of a



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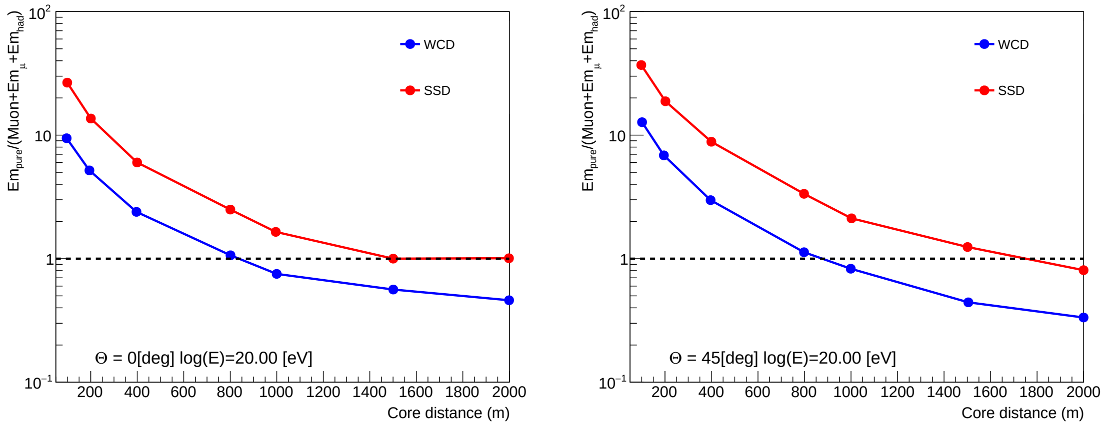


**Figure 2:** Ratios of different contributions to the integrated signal detected for air showers of $10^{20}$ eV at two zenith angles. Shown is the ratio between the electromagnetic component and the muonic component. The curve labeled "WCD" corresponds to the water-Cherenkov detectors of the Auger array, while the red one "SSD" corresponds to the scintillator detectors.

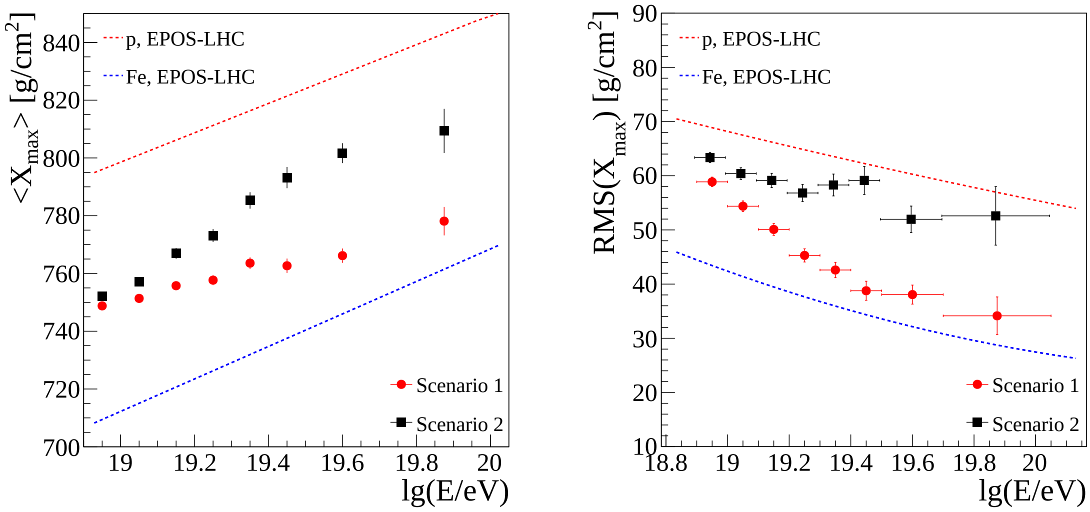


**Figure 3:** Predicted $X_{\rm max}$ and $\sigma(X_{\rm max})$ for the two benchmark scenarios ([22]. Scenario 1: maximum-rigidity; Scenario 2: photo-disintegration

sub-sample of events in the cutoff region enriched with light elements, increasing the capacity of the Observatory to identify the potential sources of UHECRs.

## 5. Status of AugerPrime and its Engineering Array

The first twelve stations of AugerPrime, 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 are partially located inside the standard 1500 m spaced array (9 detectors) and partially in the more dense area where the separation of the stations is 750 m (3

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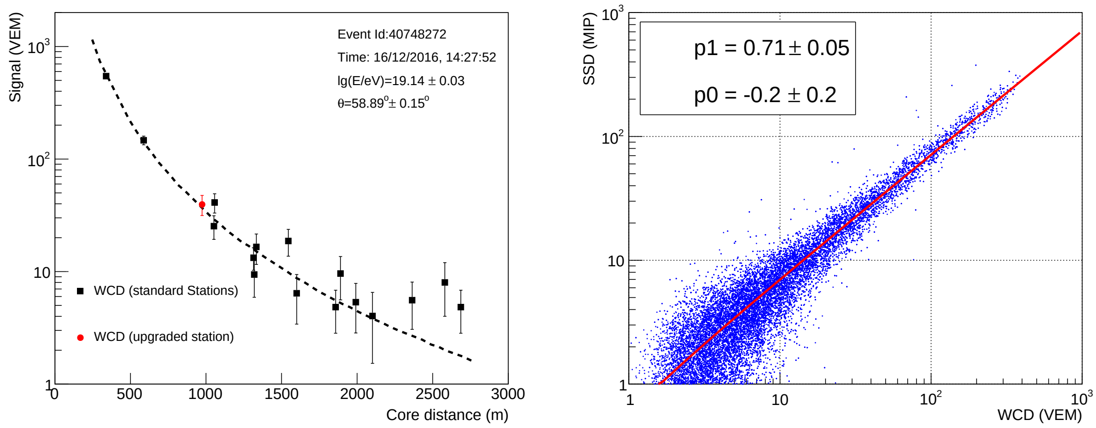


**Figure 4:** Left: one event reconstructed with the regular 1500 m array in close proximity to the EA. The reconstructed signals in the EA are compared with the LDF of the event; Right: correlation of the signals of the SSD and the WCD. Both signals have been calibrated;

detectors) [21]. The Engineering Array has been in continuous data taking mode since begin of October 2016 and has collected more that 30000 local triggers. Standard stations in the EA area have been used to reconstruct more than 3000 events, the larger fraction of them in the 750 m array [21].

The performance of the upgraded stations has been monitored with the data collected by the EA. In figure 4 (left) is shown one event collected and reconstructed with the 1500 m spaced array in the region of the EA. The reconstructed number of Vertical Equivalent Muons (VEMs) detected with an upgraded WCD is shown with a different color. The upgraded stations produce signals that are in good agreement with expectations. Figure 4 (right) shows the good correlation between the calibrated signals of the SSD and the calibrated signals in the WCD. The correlation between the two signals verifies the independent calibration procedures developed for the new detectors (see [21] for a description of the calibration procedures). The ratio of 0.7 between the signals in the two detectors is expected and is due to a combination of the geometry of the WCD and the SSD and of the response of the two detectors.

Important for the determination of the primary mass with the upgrade stations are the detectors viewing a large number of particles. To avoid saturated stations close to the shower core a strong effort in the upgrade has been dedicated to the extension of the dynamic range of the WCD and in providing a sufficient dynamic range for the new SSD [19]. In figure 5 (left) is shown the measured dynamic range of one of the SSD stations in the EA. The figure shows that the SSDs are linear within 5% up to a signal of 20000 particles. As expected, the SSDs are more sensitive to the electromagnetic component of the extensive air showers. The lateral density function (LDF) of SSD signals is higher than the corresponding LDF of the WCD in the region close to the shower axis (see figure 5 (right)). Far from the shower core the showers are dominated by the muons and the signal density in the two detectors becomes comparable. The different response of the two detectors to the two main components of the EAS is the tool for the identification of the mass of the primary cosmic rays on a event-by-event basis [13].

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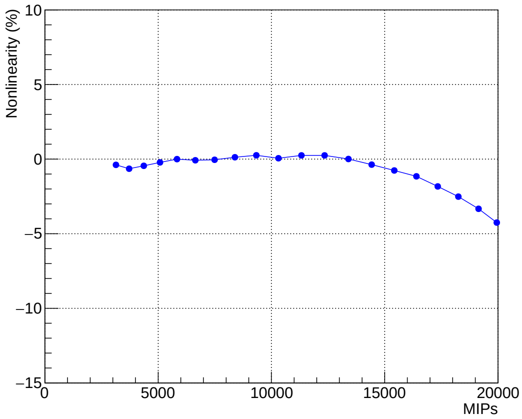


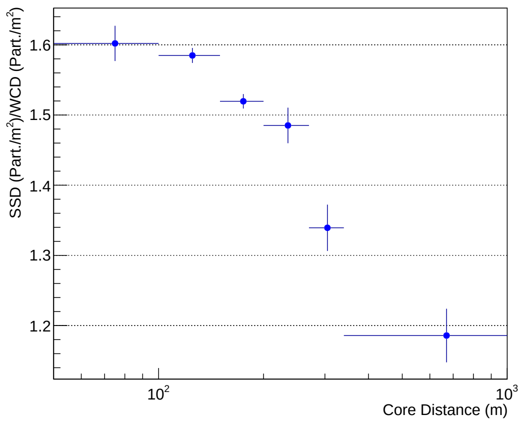


**Figure 5:** Left: Measured dynamic range of one SSD detector, the detector is linear within 5% up to 16000 particles. Right: ratio between the SSD and the WCD particle density versus the distance from the shower core (detectors without signals have been excluded)

## 6. Conclusions

AugerPrime will collect high-quality data from 2018 until 2024. In this period, the number of events collected will be comparable with the statistics collected up to now by the existing Pierre Auger Observatory, with the advantage that every future event will have mass information and will allow us to better address some of the most pressing questions in UHECR physics. Obtaining additional composition-sensitive information will help to better reconstruct the properties of the primary particles at the highest energies. Moreover, it will improve the measurements in the important energy range just above the spectral ankle. Measurements with AugerPrime will help to reduce systematic uncertainties related to the hadronic interaction models and to the reconstruction algorithms. This improved knowledge of air-shower physics will allow a reanalysis of existing data for improved energy evaluation and for improved mass composition studies. A new agreement has been signed between the funding agencies in November 2015 extending the acquisition period of the Pierre Auger Observatory until 2024 and supporting the AugerPrime upgrade. The start of the deployment of the upgraded stations is expected in January 2018.

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