AugerPrime looks for cosmic superaccelerators

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The Pierre Auger Observatory has begun a major Upgrade (AugerPrime), with an emphasis on improved mass composition determination using the surface detectors of the Observatory. AugerPrime, for the project management of which the Lecce group is responsible, will be upgraded with new scintillation detectors for a more detailed measurement of gigantic air showers. This is required to identify cosmic objects that accelerate atomic particles up to highest energies.

1. Introduction

The data taken with the Pierre Auger Observatory[1] contributed to a number of steps forward in the field of ultra-high energy cosmic rays (UHECRs)[2, 3] .

In order to extend the composition sensitivity of the Auger Observatory into the flux suppression region, an upgrade of the Auger Observatory (named AugerPrime [4, 5]) has been planned. The main aim of AugerPrime is to provide additional measurements of composition-sensitive observables, allowing to determine the primary mass of the highest energy cosmic rays on a shower-by-shower basis.

2. The Detector Upgrade

Taking data until the end of 2024 will double the present surface detector (SD) event statistics and reduce the total statistical uncertainty at the highest energies. With the planned upgraded detector running for 7 years we can expect about 700 events above 3x10^{19} eV and more than 60 above 6x10^{19} eV for zenith angles less than 60°. "Horizontal air showers"will add about 30% to the exposure and thus to the number of expected events. Accounting for a detector resolution of 15% or better in determining the number of muons, this would allow a separation of a fraction as small as 10% of protons from intermediate and heavy primaries. The key question is whether we can use additional information on the separation between the electromagnetic and muonic shower components for improving the estimate of the mass of the primary particles adding an extra measurement of the particles in the EAS independent of the measurements made with the water-Cherenkov detectors (WCD). To achieve the maximum advantage from this additional measurement, the shower should be sampled in the position of the WCD with a detector that has a different response to the basic components of the EAS. Moreover, the additional detector has to be reliable, easy to realize and install, and has to have minimal maintenance. Overall, the expectations from air shower simulations strongly indicate the feasibility of composition determination at the highest energies. It can be expected that, if the detector resolution in determining the number of muons and the X_{max} is smaller or of the order of the shower fluctuations, the primary mass can be inferred on an event-by-event basis. The main part of the upgrade is the Scintillator Surface Detector (SSD). A thin scintillation detector, which is mounted above and triggered by the larger WCD detector below it, provides a robust and well-understood way of particle detection that is sufficiently complementary to obtain a good measurement of the density of muons.

An SSD unit consists of a box of 3.8m×1.3m, containing two scintillator sub-modules, each composed of extruded polystyrene scintillator bars of about 1.6m length, 5cm width and 1cm thickness.The 4m^2 scintillator planes are housed in light-tight, weatherproof enclosures, attached to the existing WCD with a strong support frame (see Figure 1). The scintillator light will be read out with wavelength-shifting fibres inserted into straight extruded holes in the scintillator planes, which are bundled and attached to a single photomultiplier tube. Figure 2 shows how the green wavelength-shifting fibres emerge from the scin-

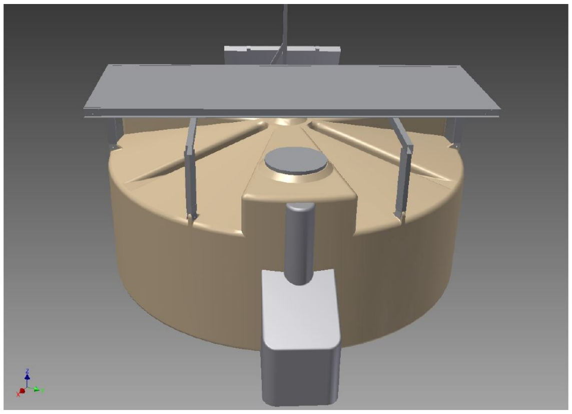

Figure 1. 3D drawing of an AugerPrime SSD station with the scintillator plane housed in a weatherproof enclosure above a WCD.

tillator planes and are grouped into bundles. As photodetector, the 8-stage, 38mm diameter photomultiplier Hamamatsu R9420 has been selected as baseline design due to its high linearity of up to 200 mA peak anode current, but other solutions are under investigation as well.

The proposed upgrade includes also an improved detector electronics, an Underground Muon Detector (UMD), and the extension of the FD measurement into hours with higher night sky background (NSB).

3. Expected Performance of the Upgrade

The number of muons is the most direct composition-sensitive and model-independent observable that can be obtained from the upgraded detector array. The signal responses to particles of the muonic and electromagnetic shower components in the two detectors (SSD and WCD) allow one to derive the muonic signal on a single station basis (matrix inversion method[6]) according to the expression:

$$S_{\mu,WCD} = aS_{WCD} + bS_{SSD}$$

where $S_{\mu,WCD}$ is the muonic signal in the WCD, S_{WCD} is the WCD signal in units of the response to a vertical equivalent muon (VEM) and S_{SSD} is the WCD signal in units of the response to minimum ionizing particle (MIP). The two factors a and b are inferred from detector simulation and are only weakly dependent on the lateral distance from the shower core and from the primary composition. Given the limited size of the detector stations, this method allows one to derive a mean muon numbers, and is affected by large fluctuations

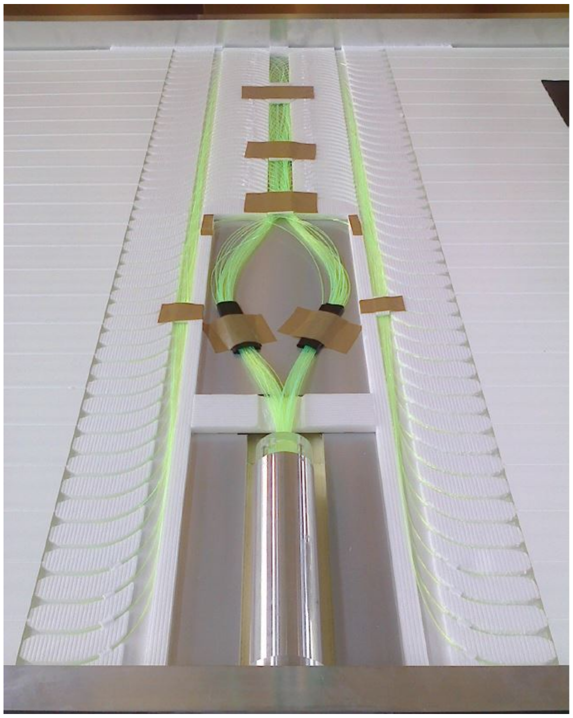

Figure 2. Photo of the inner part of a SSD detector with green wavelenght-shifting fibers routed from scintillators and guided in two bundles to the photomultiplier tube, housed in the aluminum support.

In order to reduce the statistical uncertainty of the muon density at a given distance, it is possible to fit a lateral distribution function (LDF) to the signals, and use the LDF values in the above equation. Using $S_\mu(800)$ (the muonic signal at a distance of 800 m from the core) it is possible to reach reconstruction resolutions as small as $\sigma[S_\mu(800)]/ < S_\mu(800) >\approx 22\%$ for protons and $\sigma[S_\mu(800)]/ < S_\mu(800) >\approx 14\%$ for iron at $E \approx 10^{19.8} eV$ and $\theta = 38^\circ$.

Another possible analysis is based on the shower universality method[7]. This method predicts for the entire range of primary masses the air shower characteristics on the ground using only three parameters: the shower energy, the depth of shower maximum (derived from the curvature of the shower front and the steepness of the lateral distribution) and the number of muons relative to the expectation of a reference model. Using these observables it is possible to develop an *ad hoc* reconstruction. The results of the analysis are given in the following, but it should be kept in mind that the corresponding merit factors should be considered as lower limits to what will be reached after having a better understanding of the detectors. The bias of the Xmax reconstruction is below $15g/cm^2$ with a resolution improving from $40g/cm^2$ at 10^{19} eV to $25g/cm^2$ at 10^{20} eV.

4. Science Impact of the Upgrade

One of the key questions of the physics reach of the Auger Upgrade is that of being able to discriminate different composition and, hence, 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 spectra have been chosen as representations of a maximum-rigidity scenario (scenario 1) and one photo-disintegration scenario (scenario 2), as explained in detail in [8]. A fit to the Auger flux and composition data for $E > 10^{18.7}$eV has been performed and Figure 3 illustrates the fluxes of different mass groups in these scenarios.

Figure 4 shows the mean X_{max} and the corresponding $\sigma(X_{max})$ for these spectra, using only the SD data of the upgraded array. The $\sigma(X_{max})$ contains the intrinsic air-shower fluctuations and the detector resolution. The same quantities as expected for pure proton and pure iron compositions are illustrated. The difference in the evolution of the mass compositions of the two models in the energy range of the flux suppression can be distinguished with high significance.

The fractional deviation in the mean number of muons 38° relative to that expected for an equal mix of p-He-CNO-Fe as primary particles, is shown in Figure 5.

While the mean X_{max} and $\sigma(X_{max})$ are very similar up to $10^{19.2}eV$, which corresponds to the energy range well covered by data of the fluorescence telescopes, the models predict significantly different extrapolations into the GZK suppression region and the two scenarios can be distinguished with high significance and statistics.

5. Status of the Upgrade

The first twelve SSD modules for the engineering array have been assembled in Europe and sent to the Pierre Auger Observatory, where they were deployed to the engineering array site in September 2016. The Engineering array is located inside the standard array, and for some of the WCD there are two SSD instrumented with different photodetectors (PMT and SiPM) . Preliminary results from the upgraded stations already show the first muon signals.

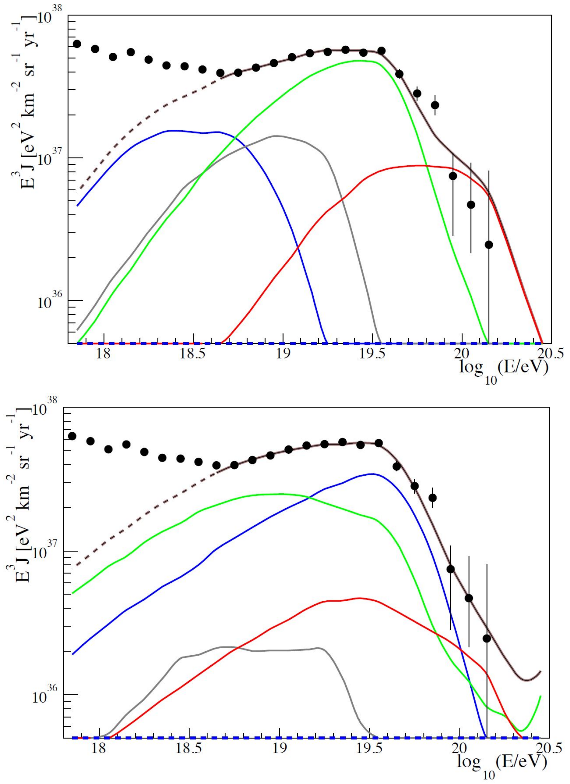

Figure 3. Examples of fluxes of different mass groups for describing the Auger spectrum and composition data. Shown are the fluxes of different mass groups that are approximations of one maximum-rigidity scenario (upper) and one photo-disintegration scenario (lower). The colors for the different mass groups are protons blue, helium gray, nitrogen green, and iron red.

6. Conclusions

AugerPrime promises high-quality future data, and real scope for new physics uses of existing events. With operation planned from 2018 until 2024, event statistics will more than double compared with the existing Auger data set, with the critical added advantage that every event will have mass information and will allow one to better address some of the most pressing questions in UHECR physics. Obtaining additional composition-sensitive information will not only help to better reconstruct the properties of the primary particles at the highest energies, but also improve the measurements in the important energy range just above the spectral ankle. Furthermore, measurements with the new detectors will help to reduce systematic uncertainties related to modeling hadronic showers and to limitations of

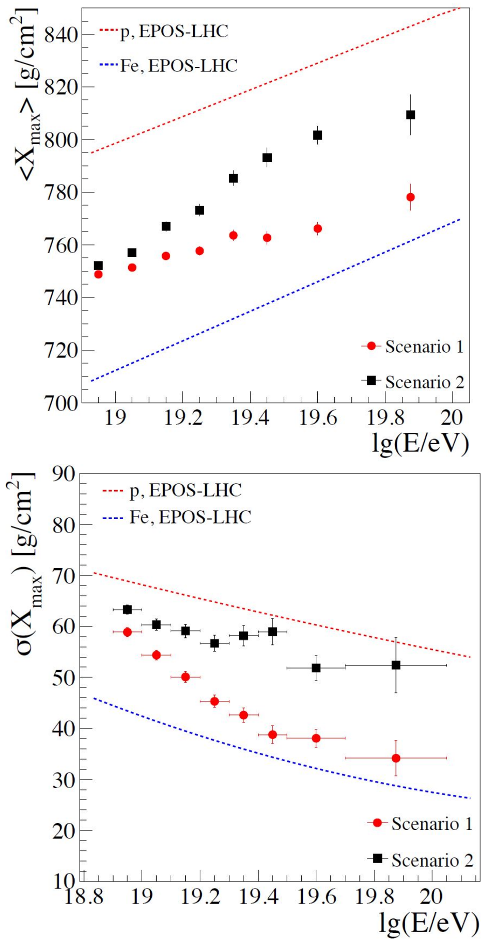

Figure 4. Reconstructed mean depth of shower maximum X_{max} (upper) and its fluctuations $\sigma(X_{max})$ (lower)

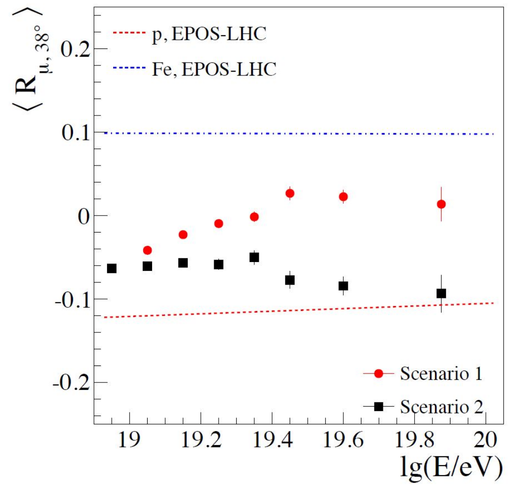

Figure 5. Fractional deviation in the mean number of muons at 38° relative to that expected for an equal mix of p-He-CNO-Fe as primary particles.

reconstruction algorithms. This improved knowledge of air-shower physics will likely then also allow a re-analysis of existing data for improved energy assignments, for mass composition studies, and for photon and neutrino searches.

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