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FROM AUGER TO AUGERPRIME: UNDERSTANDING ULTRAHIGH-ENERGY COSMIC RAYS

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Abstract. Ultrahigh-energy cosmic rays (UHECRs), whose origin is still mysterious, provide a unique probe of the most extreme environments in the universe, of the intergalactic space and of particle physics beyond the reach of terrestrial accelerators. The Pierre Auger Observatory started operating more than a decade ago. Outperforming preceding experiments both in size and in precision, it has boosted forward the field of UHECRs as witnessed by a wealth of results. These include the study of the energy spectrum beyond 1 EeV with its spectral suppression around 40 EeV, of the large-scale anisotropy, of the mass composition, as well as stringent limits on photon and neutrino fluxes.

But any harvest of new results also calls for new questions: what is the true nature of the spectral suppression: a propagation effect (so-called Greisen, Zatsepin and Kuz'min or GZK cutoff) or cosmic accelerators running out of steam? What is the composition of UHECRs at the highest energies? In order to answer these questions, the Auger Collaboration is undertaking a major upgrade program of its detectors, the AugerPrime project. The science case and motivations, the technical strategy and the scientific prospects are presented.

Keywords: Cosmic rays, UHECRs, Pierre Auger Observatory

1 Introduction

Ultrahigh-energy cosmic rays have been studied at the Pierre Auger Observatory for more than 10 years by recording the associated extensive air showers (EASs). The Observatory (The Pierre Auger Collaboration 2015a) comprises a surface detector (SD) consisting of an array of 1600 water-Cherenkov stations with a spacing of 1500 m, covering an area of ≈ 3000 km^2 and an air-fluorescence detector (FD) with a total of 24 telescopes in four sites on the perimeter of this array. The SD samples at ground level the particle components of extensive air showers with a duty cycle of nearly 100%, while the FD measures the longitudinal development of showers along their path in the atmosphere during clear moonless nights (with a duty cycle of $\sim$15%). The 1500 m spacing of the SD makes it 100% efficient to showers with energies above 3×10^{18} eV. A denser infill array, with 61 water-Cherenkov detectors on a grid of 750 m spacing, extends the energy range down to 3×10^{17} eV. Energies as low as 10^{17} eV are measured by means of 3 additional high-elevation Auger telescopes (HEAT). A sub-array of 124 radio sensors (Auger Engineering Radio Array, or AERA) working in the MHz range is employed to study radio emission from EASs and to identify mass-sensitive radio parameters.

The collected data provide information on the nature and origin of the primary cosmic rays and their astrophysical interpretation. From the point of view of particle physics, the measured observables allow us to set constraints on hadronic interactions and test their modelling in an energetic and kinematic region not reachable at accelerators. A selection of some the most important results is presented in this paper; for most of them, we refer the reader to the latest updates summarized in (The Pierre Auger Collaboration 2015b),(Ghia 2015).

2 Selected results

The energy spectrum above 3 $\times 10^{17}$ eV has been measured with unprecedented precision and statistics using 4 different data sets: the SD 'vertical' data up to a zenith angle of $\theta = 60°$, the 'horizontal' data beyond

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$\theta = 60^{\text{o}}$, the infill data and the "hybrid" data, the latter consisting of all events detected simultaneously by both the SD and FD. The hybrid data set is used to obtain the energy calibration directly from the data (The Pierre Auger Collaboration 2014a; Pesce 2011; Ravignani 2013). The resulting spectrum, shown in Fig. 1, flattens from a power law with index $3.29 \pm 0.02(\text{stat}) \pm 0.05(\text{sys})$ to one with index $2.60 \pm 0.02(\text{stat}) \pm 0.1(\text{sys})$ at $E_{\text{ankle}} = 4.8 \pm 0.1 \pm 0.8$EeV. A clear suppression is observed at a significance in excess of 20σ beyond $E_{\text{s}} = 42.1 \pm 1.7 \pm 7.6$EeV, energy at which the differential flux is reduced to one-half of the expected one from the extrapolation of the power-law above the ankle. The dominant systematic uncertainty of the spectrum stems from a 14% overall uncertainty in the energy scale.

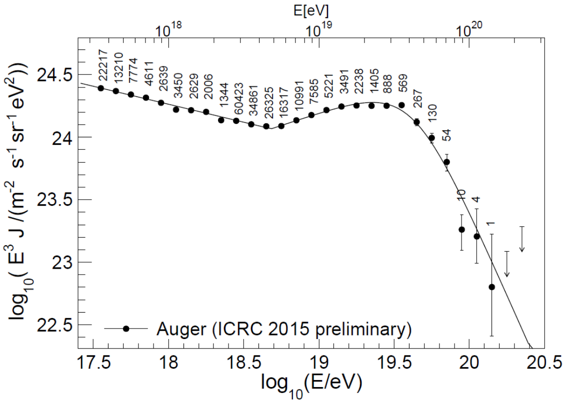

Fig. 1. The combined Auger energy spectrum.

Different observables can be used to obtain information on the primary composition, the most direct of which is the depth X_{max} of maximum development of the longitudinal shower profile, measured by the FD. Its first two moments $\langle X_{\text{max}} \rangle$ and root-mean squared RMS(X_{max}) are related to the depth of the first interaction of the primary and to the subsequent development of the shower. The interpretation in terms of composition is inferred through the comparison with simulated data obtained using different hadronic interactions models. It is therefore affected by the rather large theoretical uncertainties of theses models. Having been corrected for the detector resolution, $\langle X_{\text{max}} \rangle$ and its RMS can be directly compared to the predictions of air-shower simulations using recent hadronic interaction models, as shown in Fig. 2. Our measurements are clearly at variance with model predictions for a pure composition; assuming no change in hadronic interactions at these energies, they point to a composition getting heavier above the ankle.

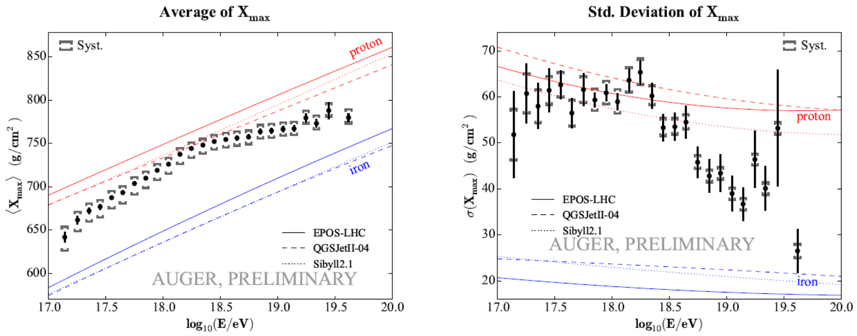

Fig. 2. First two moments of the X_{max} distribution, compared to model predictions, assuming either an all-proton or all-iron composition.

A deeper insight can be obtained by studying the shape of the X_{max} distributions (The Pierre Auger Collaboration 2014b): comparing them with those expected for different mass fractions (using different hadronic interaction models), the best fitting mixture of nuclei can be derived. This study shows that the data can be best reproduced with the inclusion of intermediate nuclei, the proton fraction strongly decreasing above 10^{19} eV, a 10-15% proton contribution seeming to appear again above $\approx 2.5 \times 10^{19}$eV. The high fraction of protons in the ankle region, together with the anisotropy limits derived from our data (The Pierre Auger Collaboration 2015c) suggest that already below $10^{18.5}$eV protons are mainly extragalactic and could point to an interpretation of the ankle as being due to the energy loss of extragalactic protons through electron-positron pair production during propagation in the cosmic microwave background Berezinsky & al. (2005, 2006). However, exploiting the correlation between $X_{\max}$ and the number of muons produced in the EAS at energies around 10^{19} eV, which is sensitive to the mixture of primary masses, we showed that the composition around the ankle is actually mixed, thus disfavouring that hypothesis.

An attempt to understand the origin of the suppression was made by simultaneously fitting both the spectrum and the evolution of $X_{\max}$ above $10^{18.7}$ eV. A simple astrophysical model was used assuming identical sources, homogeneously distributed in a comoving volume, injecting protons, He, N and Fe nuclei. The spectrum at the source was described as a broken power law with a rigidity-dependent exponential cutoff. The best fit to the spectrum was obtained by subsequent cutoffs of the different groups of elements, with $R_{\text{cut}} = 10^{18.67}$V and a very hard source spectrum with slope $\gamma = 0.94$, thus pointing to a flux suppression partly due to the reach to the maximum energy within the source. A second local minimum, with $\gamma = 2$ and larger maximum rigidity, similar to that expected for energy-loss effects due to propagation, can fit the spectrum, but the $X_{\max}$ distributions are too wide to agree with those measured. The best-fit position strongly depends on the details of propagation and of the air-shower development, the uncertainties of which are much larger than the statistical uncertainty of the measured data.

3 The AugerPrime upgrade

In the past 10 years, the Auger results have led to major breakthroughs in the study of cosmic rays. Different models have been built trying to reproduce our results (Caprioli & al. 2015; Unger & al. 2015; Globus & al. 2015), but the many unknowns about source distribution, composition, galactic and extragalactic magnetic fields, etc, prevent the emergence of a uniquely consistent picture. New information on the nature of the primaries is mandatory to address the problem of the origin of ultrahigh-energy particles. As discussed above, the origin of the flux suppression is still unknown, whether it be due to propagation effects or to exhaustion of the sources. We need mass-composition information above 40 EeV, currently not available due to the intrinsic duty cycle of the FD. Furthermore, the direct detection of cosmogenic photons or neutrinos would be direct evidence of the GZK effect. Studies of the arrival directions of UHECRs with composition-related selections will be most important to understand the reasons for the lack of small-scale anisotropy at the highest energies. The evaluation of the proton fraction above a few times 10^{19} eV is the decisive ingredient for estimating the physics potential of existing and future cosmic-ray, neutrino, and γ-ray detectors. From the particle physics point of view, direct measurements of the muon component of EASs will allow the study of hadronic interactions in an energy and kinematic region not explorable by terrestrial accelerators.

The AugerPrime upgrade of the Observatory has been specifically designed to improve the composition-sensitive information (The Pierre Auger Collaboration 2016). Along the lines of a hybrid design, each SD will be equipped with a top scintillator layer (Fig. 3a). Shower particles will be sampled by two detectors (scintillators and water-Cherenkov stations) having different responses to the muonic and electromagnetic components, thus allowing us to reconstruct each of them separately. The muonic component will be derived in each station by subtracting the signal observed in the scintillator from that seen in the water-Cherenkov tank. By fitting the muon lateral distribution, the muon signal at 800 m from the core $S(800)$ can be used as a composition-related observable. More sophisticated methods, based on multivariate analyses or on shower universality (Ave & al. 2011; Lipari 2008) will allow us to correlate the detector signals at different lateral distances and exploit the information of the arrival time of the EAS and of the temporal structure of the measured signals.

A preliminary demonstration of the potentials of AugerPrime can be obtained by taking two extreme and opposite assumptions fitted to the Auger flux and composition data: a maximum-rigidity (scenario 1) and a photo-disintegration one (scenario 2). The muon number relative to that expected for an equal mix of p-He-CNO-Fe as primary particles, the mean $X_{\max}$ and its RMS are shown in Fig. 3(b-d). Their values are quite similar in the region below $10^{19.2}$eV, covered by data of the FD, but the two scenarios can be distinguished with high significance and statistics in the GZK suppression region, where the models predict significantly different extrapolations.

The upgrade of the SD will also include newer electronics, with faster digitizers (120 MHz sampling compared to the current 40 MHz) and an increased dynamic range, allowing us to extend the measure to the larger signals closer to the shower core. To complement the SD upgrade, a network of underground muon detectors, each

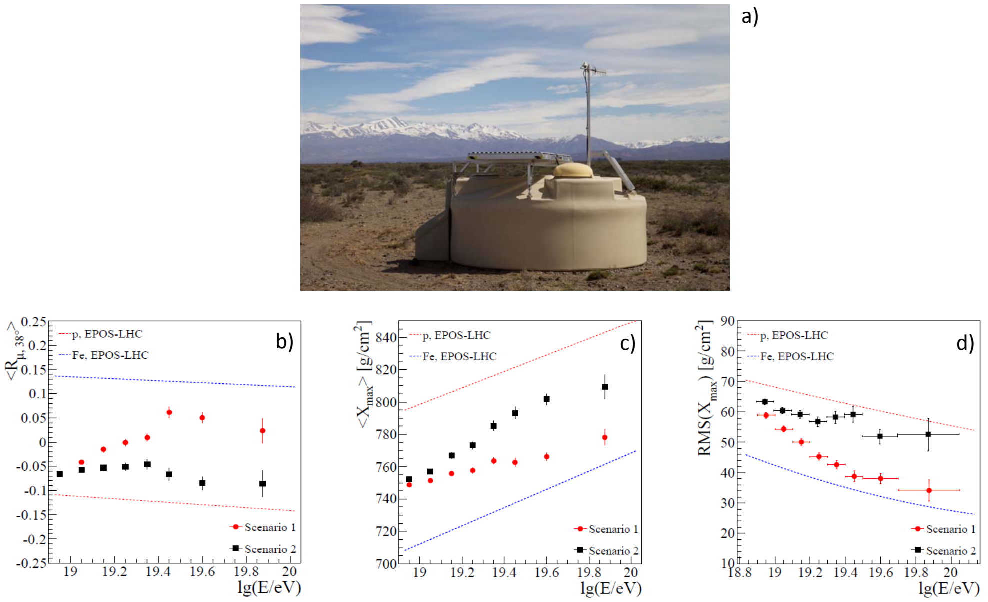

Fig. 3. (a) One of the first AugerPrime upgraded surface detectors; (b-d) reconstructed relative muon number R_μ, $X_{\rm max}$ and RMS ($X_{\rm max}$) for the 2 considered scenarios (see text).

of 30m^2 area, is now being deployed in the infill area, for mass-composition studies in the sub-ankle region and direct verification of the extraction of the muonic signals from the combination of top scintillators and water-Cherenkov tanks. An upgrade of the FD is also foreseen: the operation mode of the FD will be changed to extend measurements into night periods with a higher light background, in order to reach a 50% increase of the on-time. The AugerPrime upgrade is now undergoing its engineering array phase. Its full operation is foreseen from 2018 until 2025, when event statistics will more than double compared with the existing Auger data set, adding event-by-event mass information.

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