PROCEEDINGS OF SCIENCE

Measurement of the cosmic ray energy spectrum above 1 EeV at the Pierre Auger Observatory

PoS(EPS-HEP2011)050

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The Pierre Auger Observatory is measuring extensive air showers initiated by ultra-high energy cosmic rays from simultaneous observation of fluorescence and surface detectors with unprecedented precision. The high statistics of the surface detector allows a good determination of the cosmic ray flux above an energy of 3 EeV. This bound is extended down to 1 EeV using a unique technique that exploits the hybrid detection power. The spectrum is presented displaying two clear features in the energy range between 1 and 100 EeV.

The 2011 Europhysics Conference on High Energy Physics, EPS-HEP 2011,
July 21-27, 2011
Grenoble, Rhône-Alpes, France

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1. Introduction

Ultra High Energy Cosmic Rays (UHECR) [1] represent the most energetic elementary particles available to scientists. They have macroscopic energies, exceeding 10^{18} eV, but their flux is very weak, one particle per century per square kilometre for the highest energies. When high-energy cosmic rays enter the Earth's atmosphere, they interact with the air and initiate cascades of secondary particles, the extensive air showers (EAS). Air shower detectors derive information about the primary cosmic particle from the measurement of the EAS.

Understanding the nature and the origin of the UHECR is the objective of the Pierre Auger Observatory [2] which brings unique capabilities to their study. Designed as an hybrid detector, it uses two techniques to measure the EAS properties by observing both their longitudinal development in the atmosphere and their lateral spread at ground level. The Observatory is located in the southern hemisphere, in the province of Mendoza (Argentina) and covers 3000 km^2, being the largest cosmic ray detector in operation. Charged particles and photons that reach the ground are sampled with the Surface Detector array (SD) which consists of 1660 independent water Cherenkov detectors, spread on a triangular grid of 1.5 km spacing over the area. The fluorescence light generated in the atmosphere by the charged particles of the air shower through excitation of N_2 molecules is detected by the Fluorescence Detector (FD) which consists of 27 telescopes. The FD can only operate during clear moonless nights which limits its duty cycle to 13% [3] while the SD operates 24 hours per day. The Observatory, completed in mid-2008, provides a huge collecting area; data taking started already in January 2004 and was continuing as it grew in size.

2. Air shower reconstruction and energy determination

For the spectrum measurement described in the present contribution, only showers with zenith angle below 60° are used. About one air shower out of ten that reach the SD is also observed by the FD. The reconstruction of hybrid events employs, besides the information from the FD telescope, the timing information of one surface detector, resulting in a good angular resolution of 0.6° above 1 EeV. The FD provides a nearly calorimetric measurement of the cosmic ray energy: the energy deposit as a function of traversed matter in the atmosphere is obtained from fluorescence and Cherenkov light contributions, taking into account the attenuation and the multiple scattering in the atmosphere. The energy of the cosmic ray is the integral over the entire longitudinal profile with a correction for the "unseen" energy carried away by the neutrinos and muons which cannot be measured by the FD. The energy resolution for the hybrid events is 7.6% above 1 EeV. The systematic uncertainty on the energy assignment is estimated to be about 22%, resulting from the uncertainties on the fluorescence yield (14%), the knowledge of atmospheric conditions (8%), the absolute detector calibration (9.5%), the shower reconstruction (10%) and the unseen energy (4%).

The air shower axis of events detected by the SD is obtained from the arrival time of the particles in each surface detector. The angular resolution is better than 1° for events that triggered more than 6 stations. The shower impact point on the ground and the lateral distribution of signals are obtained in a global likelihood minimization. The signal at 1000 m, where the fluctuations of the lateral distribution function are minimized, is corrected for the attenuation in the atmosphere for showers with different zenith angle by the constant intensity cut method [4], and is rescaled to the common parameter S_{38} used as the SD energy estimator.

The energy calibration of SD data is obtained from the events reconstructed with both the surface and the fluorescence detectors [5]. The correlation curve of the respective energies shows a power law dependency between S_{38} and E_{FD}. Thanks to the hybrid concept of the detector, the calibration procedure is almost independent of air shower simulations. The SD energy resolution obtained from the distribution of $\frac{E_{SD}}{E_{FD}}$ varies from 16% at threshold to 12% for $E > 10$ EeV.

3. Energy spectrum

The selection criterion applied on the SD events used for the energy spectrum is that the station with the highest signal should be surrounded by 6 active stations. The SD exposure is obtained by integrating the area covered by active stations over time [6]. The acceptance is saturated, regardless of primary mass, above 3 EeV, and is free of simulation assumptions. From Jan. 2004 to Dec. 2010, the exposure is 20905 km^2 sr yr (60% larger than that used in the previously published spectrum [8]), with an uncertainty of 3% [5]. Due to the energy resolution, the bin-to-bin migration has an impact on the flux reconstruction and the spectral shape of the spectrum. The correction of this effect, performed with a foward folding approach, is less then 20% on the considered energy range. The total systematic uncertainty on the flux is 6%, and the absolute energy scale is affected by a systematic error of 22% due to the uncertainty on the fluorescence energy assignment.

The energy spectrum can be extended down to 1 EeV, thanks to the hybrid events. Showers are selected only if they verify strict quality criteria and anti-bias cuts to minimize the influence of mass composition on the exposure. The energy dependent hybrid exposure is computed using an accurate time dependent Monte-Carlo simulation to reproduce, within 10 min time intervals, the FD and SD status, the measured atmospheric conditions, and the actual data taking conditions [7]. The hybrid exposure is doubled w.r.t. the one in our previous publication [8]. The systematic uncertainty in the hybrid spectrum is dominated by the exposure calculation and reaches 10% at 1 EeV and 6% above 10 EeV.

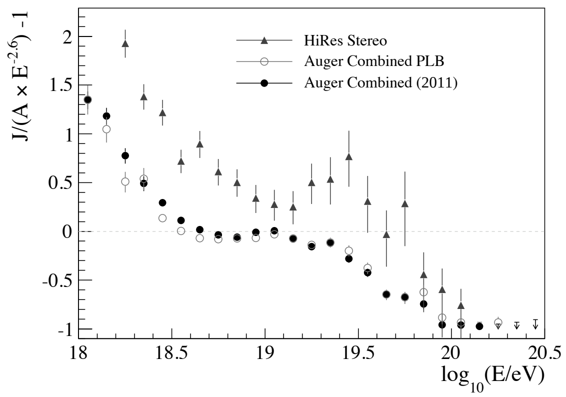

Figure 1: Fractional difference between the combined energy spectrum of the Pierre Auger Observatory and a spectrum with an index of 2.6. Measurements from the HiRes experiment [9] are shown for comparison.

A very good agreement between the energy spectrum derived from hybrid data and the one from SD data is obtained, and the two spectra are combined using a maximum likelihood method. Since the SD energy estimator is calibrated with hybrid events, the systematic uncertainty of 22% in the energy scale is common to the two spectra. The normalisation uncertainties which are independent, are used as additional constraints in the combination. Fractional difference between the combined energy spectrum and an assumed pure power-law spectrum with an index of 2.6 is shown in Fig.1, as well as the Auger spectrum published in [8]. The measurements in stereo mode from the HiRes experiment [9] are also plotted for comparison. An energy shift within the current systematic uncertainties of the energy scale applied to one or both experiments could account for most of the difference between the spectra.

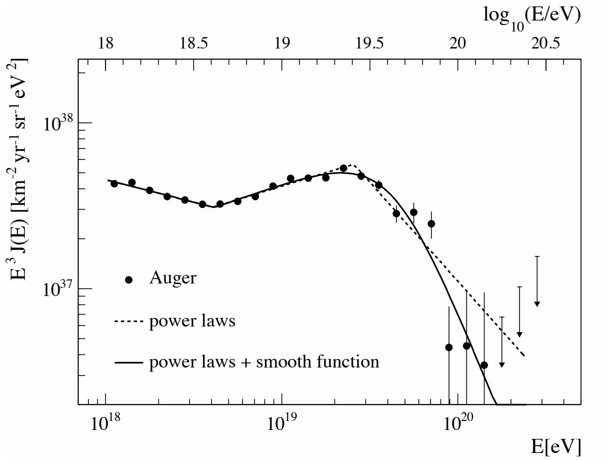

Figure 2: The combined energy spectrum fitted by 3 power laws, or by 2 power laws and a smoothly changing function at higher energies.

The combined spectrum has been fitted in two ways (Fig.2) [5, 8]. The break corresponding to the *ankle* is located at $\log_{10}(E/\text{eV}) = 18.61 \pm 0.01$. Traditionally attributed to the transition from the galactic component to a flux dominated by extragalactic sources [10], the ankle is considered in alternative scenario as a result of $e^{\pm}$ production from extragalactic protons interacting with the CMB photons [11]. The observed flux suppression above 40 EeV is compatible with the predicted degradation in the energy due to strong UHECR interactions with CMB radiation known as GZK effect [12], but it may also be related to the maximum energy achievable at nearby acceleration sites.

The Pierre Auger Collaboration has also obtained results concerning the mass composition of UHECR flux [13], needed to constrain model scenarios, and is extending its Observatory with new detection systems to investigate the cosmic rays spectrum down to $E > 0.1$ EeV [14].

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