Measurement of the UHECR energy spectrum with The Pierre Auger Observatory

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1. Introduction

Two complementary techniques are used at the Pierre Auger Observatory to detect extensive air showers initiated by ultra-high energy cosmic rays (UHECR): a surface detector array (SD) and a fluorescence detector (FD). The "hybrid" detection mode combines the information from the two subsystems.

The energy spectrum of hybrid events is determined from data taken between November 2005 and May 2008, during which the Auger Observatory was still under construction. Using selection criteria that are set out below, the exposure accumulated during this period was computed and the flux of cosmic rays above 10^{18} eV determined. The spectrum obtained with the surface detector array, updated using data until the end of December 2008, is combined with the hybrid one to obtain a spectrum measurement over a wide energy range with the highest statistics available. The flux of ultra-high energy cosmic rays exhibits two important features. At energies above 4×10^{19} eV a suppression of the flux with respect to a power law extrapolation is found, which is compatible with the predicted Greisen-Zatsepin-Kuz'min (GZK) effect, but could also be related to the maximum energy that can be reached at the sources. A break in the power law, called the ankle, is observed at an energy of about 3×10^{18} eV. This break in the energy spectrum has traditionally been attributed to the transition from the galactic component of the cosmic ray flux to a flux dominated by extragalactic sources. In recent years it became clear that a similar feature in the cosmic ray spectrum could also result from the propagation of protons from extragalactic sources, placing the transition from galactic to extragalactic cosmic rays at a much lower energy. The measurement of the energy spectrum and of its peculiar features is then relevant for the understanding of the nature and the origin of cosmic rays.

The group of Lecce is deeply involved in this analysis at all levels. Following references [1,2], the main activities of the group concerning this topic are outlined and summarized below.

2. Event Selection

To ensure good energy reconstruction only events that satisfy the following quality criteria are accepted:

- Showers must have a reconstructed zenith angle smaller than 60°.
- In the plane perpendicular to the shower axis, the reconstructed shower core must be within 1500 m of the station used for the geometrical reconstruction.
- The contribution of Cherenkov light to the overall signal of the FD must be less than 50%.
- The Gaisser-Hillas fit of the reconstructed longitudinal profile must be successful with $\chi^2/\mathrm{ndof} < 2.5$.
- The maximum of the shower development, X_{max}, must be observed in the field of view of the telescopes.
- The uncertainty in the reconstructed energy, which includes light flux and geometrical uncertainties, must be $\sigma(E)/E < 20\%$.
- Only periods during which no clouds were detected above the Observatory are used.

To avoid a possible bias in event selection due to the differences between shower profiles initiated by primaries of different mass, only showers

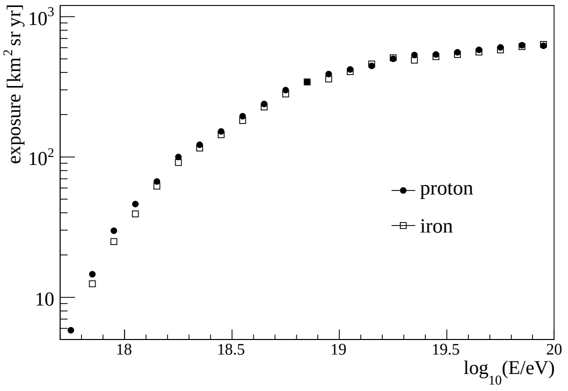

Figure 1. Hybrid exposure between November 2005 and May 2008 for proton and iron primary particles.

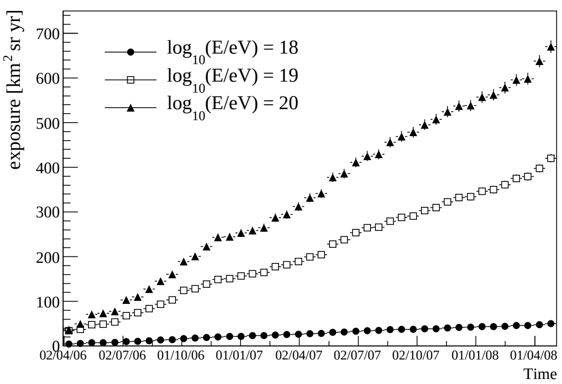

Figure 2. The growth of the hybrid exposure as a function of time starting from April 2006 up to May 2008 for three different energies.

with geometries that would allow the observation of all primaries in the range from proton to iron are retained in the data sample. The corresponding fiducial volume in shower-telescope distance and zenith angle range is defined as a function of the reconstructed energy and has been verified with data. About 1700 events fulfill the selection criteria for quality and for fiducial volume.

3. The hybrid Exposure

The hybrid exposure is shown in figure 1 for both proton (full circles) and iron (open squares) primaries. It is calculated for the data period between November 2005 and May 2008, and is that used for the hybrid energy spectrum measurement published in [3]. The analysis of the Central Laser Facility shots has revealed a systematic shift in the on-time calculation. To take account of this effect the exposure has been reduced by 4%. Moreover the end-to-end comparison has shown that the ratio of the true event rate to that expected from Monte Carlo is 0.92 ± 0.02. The systematic uncertainty of this comparison has been estimated to be ± 5%. Consequently the exposure has been reduced by half of the corresponding correction ($\sim$ 4%) to cover the full range of expectations. These two corrections are included in the exposure shown in figure 1.

A mixed composition of 50% proton and 50% iron nuclei has been assumed in the exposure calculation [3]. The remaining composition dependence has been included in the systematic uncertainty. This was found to be about 8% at 10^{18} eV decreasing down to 1% above 10^{19} eV. The dependence of the exposure on the hadronic interaction model has been also studied. The effect is smaller than 2% over the entire energy range used for the calculation of the exposure. The dependence of the exposure on the different input spectra used in the Monte Carlo simulation has also been investigated and found to be smaller than 2%. The overall systematic uncertainty on our knowledge of the hybrid exposure has been obtained by summing all these contributions in quadrature. It ranges from about 10% at 10^{18} eV to 6% above 10^{19} eV.

In figure 2, the growth of the hybrid exposure as a function of time is shown for three different energies. The increase with time shown at each energy comes as a result of the concurrence of different effects, i.e the accumulation of data taking with time and the growth of the SD array. One can also observe faster changes corresponding to the longer FD data-taking periods in the austral winter. The effect due to the growth of the SD array is more marked at higher energies where a larger hybrid detection volume is accessible with the new SD stations.

4. The hybrid energy spectrum

The measured flux as function of energy is shown in Fig. 3.

A break in the power law of the derived energy spectrum is clearly visible. The position of this feature, known as the ankle, has been determined by fitting two power laws $J = kE^{-\gamma}$ with a free break between them in the energy interval from 10^{18} eV to $10^{19.5}$ eV. The upper end of this interval was defined by the flux suppression observed in the spectrum derived using surface detector data. The ankle is found at $\log_{10}(\mathrm{E}_{ankle}/\mathrm{eV}) = 18.65 \pm 0.09(\mathrm{stat})^{+0.10}_{-0.11}(\mathrm{sys})$ and the two power

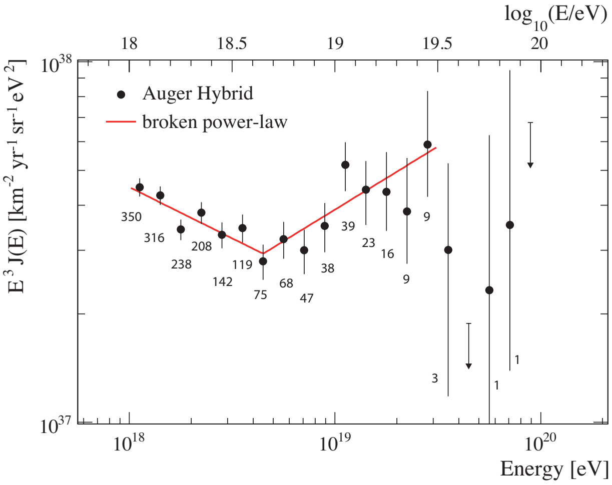

Figure 3. The energy spectrum of ultra-high energy cosmic rays determined from hybrid measurements of the Pierre Auger Observatory. The number of events is given for each of the energy bins next to the corresponding data point. Only statistical uncertainties are shown. The upper limits correspond to the 68% CL. A fit with a broken power law is used to determine the position of the ankle.

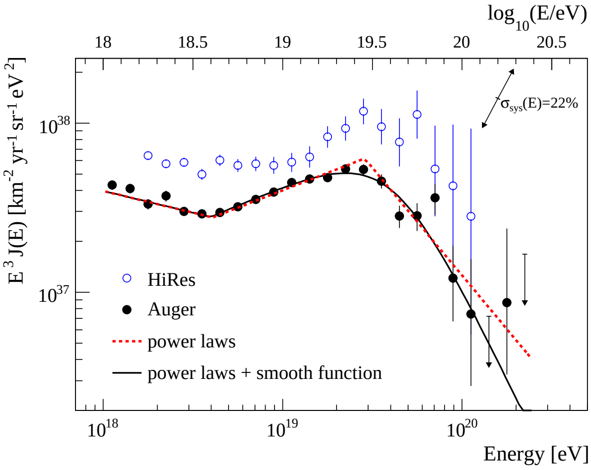

Figure 4. The combined energy spectrum is compared to data from the HiRes instrument [6]. The systematic uncertainty of the flux scaled by E^3 due to the uncertainty of the energy scale of 22% is indicated by arrows.

law indices have been determined as $\gamma_1 = 3.28 \pm 0.07(\text{stat})^{+0.11}_{-0.10}(\text{sys})$ and $\gamma_2 = 2.65 \pm 0.14(\text{stat}) \pm 0.07(\text{stat})^{+0.16}_{-0.14}(\text{sys})$ ($\chi^2/\text{ndof} = 10.2/11$), where the systematic uncertainty is due to the residual effect of the unknown mass composition. The energy estimation of fluorescence measurements relies on the knowledge of the fluorescence yield. Here we adopt the same absolute calibration and the wavelength and pressure dependence as in Ref.[4]. This is currently one of the dominant sources of systematic uncertainty (14%). The fraction of the energy of the primary particle that is carried by muons and neutrinos and does not contribute to the fluorescence signal has been calculated based on air shower simulations and goes from about 14% at 10^{18} eV to about 10% at 10^{19} eV. The systematic uncertainty depending on the choice of models and mass composition is about 8%. Further systematic uncertainties in the absolute energy scale are related to the absolute detector calibration (9.5%) and its wavelength dependence (3%). Uncertainties of the lateral width of the shower image and other reconstruction uncertainties amount to about 10% systematic uncertainty in the energy determination. Atmospheric conditions play a crucial role for air shower observations with fluorescence detectors. An extensive program of atmospheric monitoring is conducted at the Pierre Auger Observatory allowing the determination of the relevant parameters and the associated uncertainties. The total systematic uncertainty in the energy determination is estimated as 22%[5]. Indirect methods of determining the energy scale, which do not involve the fluorescence detector calibration, seem to indicate an energy normalisation that is higher than the one used he

5. The combined Auger Spectrum

The energy spectrum derived from hybrid data is combined with the one obtained from surface detector data using a maximum likelihood method. Since the surface detector energy estimator is calibrated with hybrid events, the two spectra have the same systematic uncertainty in the energy scale. On the other hand, the normalisation uncertainties are independent. They are taken as 6% for the SD and 10% (6%) for the hybrid flux at 10^{18} eV ($> 10^{19}$ eV). These normalisation uncertainties are used as additional constraints in the combination. This combination procedure is used to derive the scale parameters, k, for the fluxes that are to be applied to the individual spectra. These are $k_{SD} = 1.01$ and $k_{FD} = 0.99$ for the surface detector data and hybrid data respectively, showing that agreement between the measurements is at the 1% level. The combined energy spectrum scaled with E^3 is shown in Fig.4 in comparison with the spectrum obtained with stereo measurements of the HiRes instrument [6]. 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. The ankle feature seems to be somewhat more sharply defined in the Auger data. This is possibly due to a systematic energy offset between the experiments. However, for a complete comparison, care must also be taken to account for energy resolution and possible changes in aperture with energy.

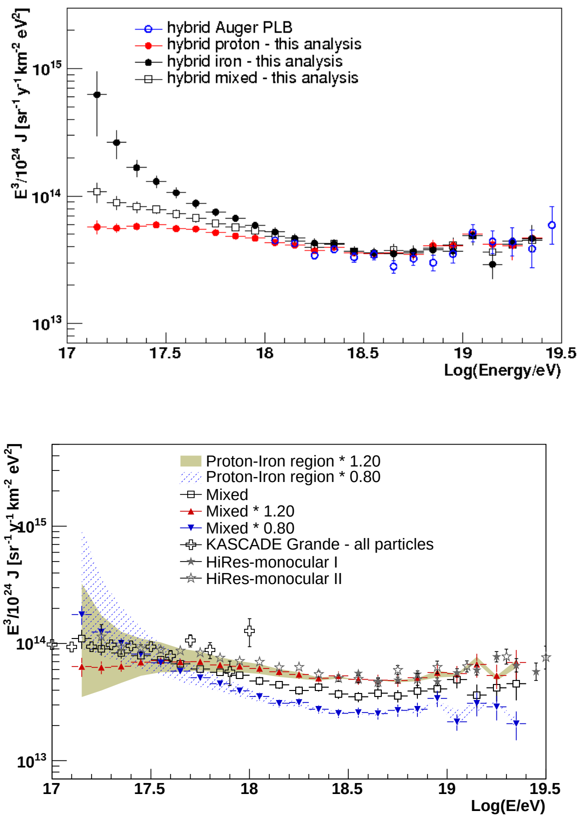

Figure 5. Top: Hybrid spectrum derived between July 2007 and March 2009, as data are pure proton (red dots), pure iron (black filled square) or mixed composition (empty squares). Bottom: Energy spectrum scaled by factor 20% upwards and downwards to estimate the impact of the systematics on the energy scale. The region between the pure proton and pure iron assumptions are drawn as filled shaded area (correcting factor 1.20) and dashed shaded area (correcting factor 0.80). Results from HiResI, HiResII and KASCADE-Grande are also shown for comparison.

6. Extension to lower energies

The extension of the energy spectrum at energy lower than 10^{18} has been performed in [7]. This energy range is relevant from the astrophysical point of view as the existence of a second *knee* is predicted by a wide class of astrophysical models. Moreover, a cross-calibration of the Pierre Auger Observatory with other experiments operating at lower energy would reinforce the results and help clarifying the open points concerning the nature and the origin of cosmic rays. Nevertheless, the expected systematic uncertainties due the lack of knowledge on the mass composition of primary particles makes the extension of the energy spectrum to lower energies very challenging. In Fig.5 (top panel), the spectra derived assuming that data are pure proton (red bullets), pure iron (black bullets) or mixed composition (empty squares) are shown for the time window between July 2007 and March 2009.

The impact of the uncertainty on the energy scale on the spectrum has been also investigated. Fig. 5 (bottom panel) shows the spectrum assuming a mixed composition with energy shifted by +20% (upward triangles) and -20% (downward triangles). The two shaded area define the region between the pure proton and pure iron options. As can be seen, the agreement with HiRes and KASCADE-Grande improves when the energy is increased of about 20%. It is worth noticing that, even if the results of all experiments agree within their systematic uncertainties, there are evidences that the current Auger energy scale is underestimated.

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