

# Measurement of the cosmic ray spectrum above $4 \times 10^{18}$ eV using inclined events detected with the Pierre Auger Observatory

## The Pierre Auger Collaboration

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**Abstract.** A measurement of the cosmic-ray spectrum for energies exceeding  $4 \times 10^{18}$  eV is presented, which is based on the analysis of showers with zenith angles greater than  $60^\circ$  detected with the Pierre Auger Observatory between 1 January 2004 and 31 December 2013. The measured spectrum confirms a flux suppression at the highest energies. Above  $5.3 \times 10^{18}$  eV, the “ankle”, the flux can be described by a power law  $E^{-\gamma}$  with index  $\gamma = 2.70 \pm 0.02$  (stat)  $\pm 0.1$  (sys) followed by a smooth suppression region. For the energy ( $E_s$ ) at which the spectral flux has fallen to one-half of its extrapolated value in the absence of suppression, we find  $E_s = (5.12 \pm 0.25$  (stat) $_{-1.2}^{+1.0}$  (sys))  $\times 10^{19}$  eV.

**Keywords:** Pierre Auger Observatory, ultra-high energy cosmic rays, inclined extensive air showers, energy spectrum

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## 1 Introduction

The Pierre Auger Observatory is to date the largest detector of air showers induced by the ultra-high energy cosmic rays (UHECRs). It is a hybrid detector combining an array of surface detectors (SD) described in detail in [1, 2] and a fluorescence detector (FD) described in [3]. Both are overseeing an area of 3000 km<sup>2</sup> near Malargüe, Province of Mendoza, Argentina, at an altitude of about 1400 m above sea level and at an average geographic latitude of 35.2° S. The redundancy provided by the two detection techniques has proved to be extremely valuable for a wide range of applications and has improved the performance of the Observatory beyond expectations.

The data gathered at the Pierre Auger Observatory with zenith angles less than 60° have provided a measurement of the UHECR spectrum [4] with unprecedented statistics. The technique developed exploits the large aperture of the SD, operating continuously, as well as the calorimetric measurement of the energy deposit obtained with the FD which is, by contrast, rather limited in duty cycle to clear nights without moonlight (13%). A parameter quantifying the shower size is obtained from the SD. This parameter is then calibrated using the energy inferred from the calorimetric FD measurement for a sub-sample of the events (hybrid events) which are detected and reconstructed simultaneously with both techniques [4]. The spectrum obtained is consistent with the Greisen and Zatsepin-Kuz'min (GZK) suppression [5, 6]. In addition, the spectrum has been independently measured using hybrid events which are detected with the fluorescence technique and at least one particle detector [7]. The latter measurement has also been combined with the SD spectrum to obtain a spectrum extending to lower energies, which has confirmed the flattening of the spectral slope at about  $5 \times 10^{18}$  eV, often referred to as the “ankle” [7, 8].

Atmospheric showers with large zenith angles have been observed since the 1960s and have stirred much interest [9], but the first reliable methods for event reconstruction are relatively recent [10, 11]. These events provide an independent measurement of the cosmic-ray spectrum. As a result they provide a direct measurement of the muon content of the showers with implications for photon searches [12, 13] and mass composition measurements [14, 15]. Extending the range of zenith angles explored to beyond 60° enhances the sky coverage [16, 17], opening regions that would otherwise be inaccessible to a surface detector. In addition these events constitute the main background for searches for ultra-high energy neutrinos using air showers [18].

Inclined shower data are reconstructed using a procedure that differs from that used to reconstruct events with zenith angles less than  $60^\circ$ , since muons in the shower front develop a pattern which is affected by the geomagnetic field [19, 20]. First, the arrival direction of the shower is obtained by fitting the arrival times of the signals at all triggered stations. The two-dimensional muon patterns at the ground can be inferred from simulations, and the distribution of the measured signals is used to obtain the shower size parameter,  $N_{19}$ , and the position of the shower axis [11]. This is possible since simulations show that, for a fixed arrival direction, the muon patterns are approximately independent of the primary composition and hadronic model assumptions, apart from a normalisation constant which establishes the muon size of the shower [11, 21]. The parameter  $N_{19}$  is defined as a constant characterising the size of the shower relative to a mean reference distribution, parameterised from proton primaries with an energy of  $10^{19}$  eV simulated using QGSJETII-03 [22] as the hadronic model.  $N_{19}$  is thus expected to be correlated with the shower energy. The energy of events is obtained by calibrating  $N_{19}$  to the calorimetric energy measured with the fluorescence telescopes [11], corrected by adding the so-called “invisible energy”. The latter accounts for the energy carried by penetrating particles, estimated using an unbiased and model-independent method [23], following closely the procedure used for events with zenith angles less than  $60^\circ$  [4]. The whole reconstruction and calibration procedure is described in full detail in [11].

In this article we present the measurement of the cosmic-ray spectrum derived from events with zenith angles between  $60^\circ$  and  $80^\circ$  detected with the Pierre Auger Observatory in the time period from 1 January 2004 to 31 December 2013.

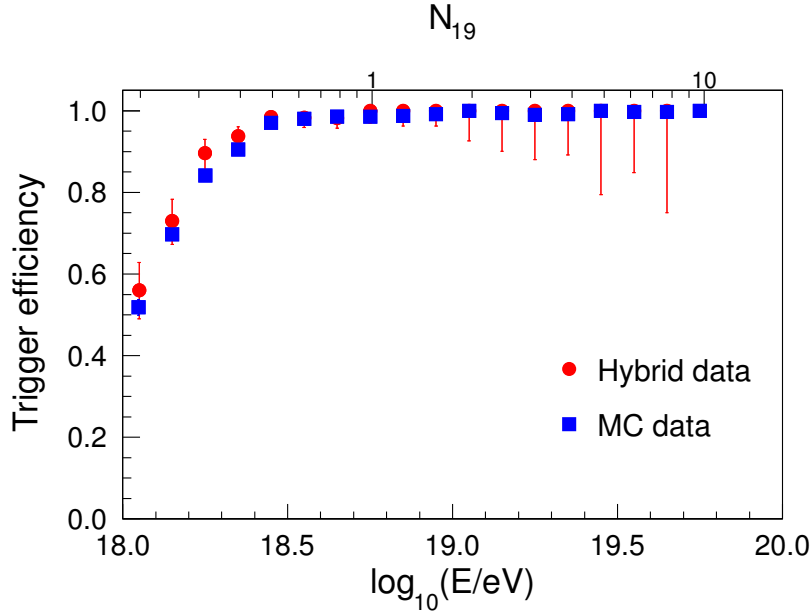
## 2 Efficiency and exposure

The spectral flux of cosmic rays is obtained by dividing the energy distribution of events by the corresponding exposure. The exposure involves the time integral of the aperture, that is, the integral of the instantaneous effective area of the SD over solid angle and observation time. This integral is subsequently weighted by the trigger and event selection efficiency, which depends on the characteristics of the shower such as the nature of the primary particle, its energy and arrival direction. For low energies, the efficiency is smaller than one due to the trigger and the selection procedures [11, 24] and can in practice be a source of large uncertainty. It is thus advantageous to limit the spectral measurements to energies at which the array is fully efficient (above the so-called threshold energy), that is, when the effective area of the SD coincides with the geometrical one.

The inclined SD data set used to measure the cosmic-ray spectrum is composed of events selected to have zenith angles between  $60^\circ$  and  $80^\circ$  and falling inside an active region of the array to guarantee that no crucial part of the shower is missing. Hence, the trigger and event selection efficiency of the SD array for inclined showers is the probability that a cosmic-ray shower reaching an active region of the array induces a trigger, is selected and finally reconstructed. Details of the triggering conditions are given in [11].

The threshold energy for a fully-efficient trigger can be determined using hybrid events (detected with the FD and having at least one triggered SD station). To avoid biases from the primary composition, the same data selection criteria as for the energy calibration [11] are applied. Additionally, it is required that the shower core reconstructed with the FD technique fall within an active cell, defined as an active station with six active neighbour stations in the regular hexagonal pattern [24]. Assuming that the detection probabilities of





**Figure 1.** Trigger and event selection efficiency of the SD array for showers with zenith angles between  $60^\circ$  and  $80^\circ$  as a function of shower energy derived from the hybrid data (circles) and from the Monte Carlo simulated showers (squares). The error bars indicate the statistical uncertainty (the 68% probability contour).

the SD and FD detectors are independent, the average detection efficiency as a function of calorimetric shower energy reconstructed with the FD can be estimated from the fraction of hybrid events that trigger the SD, are selected and finally reconstructed [11].

The efficiency can also be derived from shower simulations. A sample was used consisting of 20 000 proton showers simulated with CORSIKA [25] using QGSJETII-04 [26] with zenith angles isotropically distributed between  $60^\circ$  and  $80^\circ$  and energies ranging from  $\log_{10}(E/eV) = 18$  to 20, in steps of 0.5 (with a spectral index  $\gamma = 1$  in each sub-interval). To generate the simulated events, these showers subsequently underwent a full simulation of the detector response, within the `Offline` framework [27] of the Pierre Auger Observatory, with random impact points in the SD array. Only showers with impact points in an active region of the array are considered in the data set used for the spectrum.

For inclined showers of a given arrival direction the trigger efficiency practically depends only on the total number of muons at the ground, which is proportional to the reconstructed shower size parameter  $N_{19}$ . A recent study has reported the measurement of the muon number in inclined showers ( $62^\circ < \theta < 80^\circ$ ) at ground level, which exceeds expectations obtained with simulations and various hadronic interaction models (even when assuming a pure iron composition) [15]. To carry out a comparison between both methods used for the efficiency calculation, the energy of each simulated event is rescaled to match the corresponding shower size ( $N_{19}$ ) seen in the data. This rescaling removes the dependence of the efficiency on cosmic-ray mass composition. From simulations the average detection efficiency as a function of shower energy (true rescaled energy) is estimated from the fraction of simulated events that trigger the SD, are selected and finally reconstructed.

The efficiencies estimated with the two methods are compared in figure 1 as a function of both shower energy  $E$  and shower size parameter  $N_{19}$ . The conversion of  $N_{19}$  to energy

has been made using the calibration discussed in the next section. The efficiency evaluated with the hybrid approach is subject to relatively large uncertainties, indicated as error bars, which are due largely to the limited number of events. Both analyses agree on the trigger efficiency of the SD array, which is found to be fully efficient ( $>98\%$ ) for energies above  $4 \times 10^{18}$  eV or for  $N_{19} > 0.7$ . This value will be used as our estimate of the threshold energy of full efficiency.

The choice of a fiducial trigger based on active hexagons allows us to exploit the regularity of the array [24]. The geometrical aperture of the array is obtained as a multiple of the aperture of an elemental hexagon cell (“active unit cell”). Above the threshold energy of full efficiency, the detection area per unit cell<sup>1</sup> is  $1.95 \text{ km}^2$ , which results in an aperture of  $a_{\text{cell}} = 1.35 \text{ km}^2 \text{ sr}$  for showers with zenith angles between  $60^\circ$  and  $80^\circ$ . The calculation of the integrated exposure over a given period of time simply amounts to counting the active cells as a function of time,  $N_{\text{cell}}(t)$ , and integrating the corresponding aperture,  $N_{\text{cell}}(t) \times a_{\text{cell}}$ , over time. The overall uncertainty on the integrated exposure is less than 3% [24].

In January 2004 the initial area spanned by the array was about  $34 \text{ km}^2$  and it rose steadily until August 2008 when all 1600 surface detectors were in operation. The calculation of the surface area is the same as that used for the spectrum measured with events at zenith angles less than  $60^\circ$  and has been done numerically, making use of the trigger rate at each station [24]. The integrated exposure for showers with zenith angles between  $60^\circ$  and  $80^\circ$  amounts to  $(10\,890 \pm 330) \text{ km}^2 \text{ sr yr}$  in the time period from 1 January 2004 to 31 December 2013 (which corresponds to 29% of the exposure for showers with  $\theta < 60^\circ$  in the same period). This calculation excludes periods during which the array was not sufficiently stable, which add up to a small fraction of the total time (of the order of 5%).

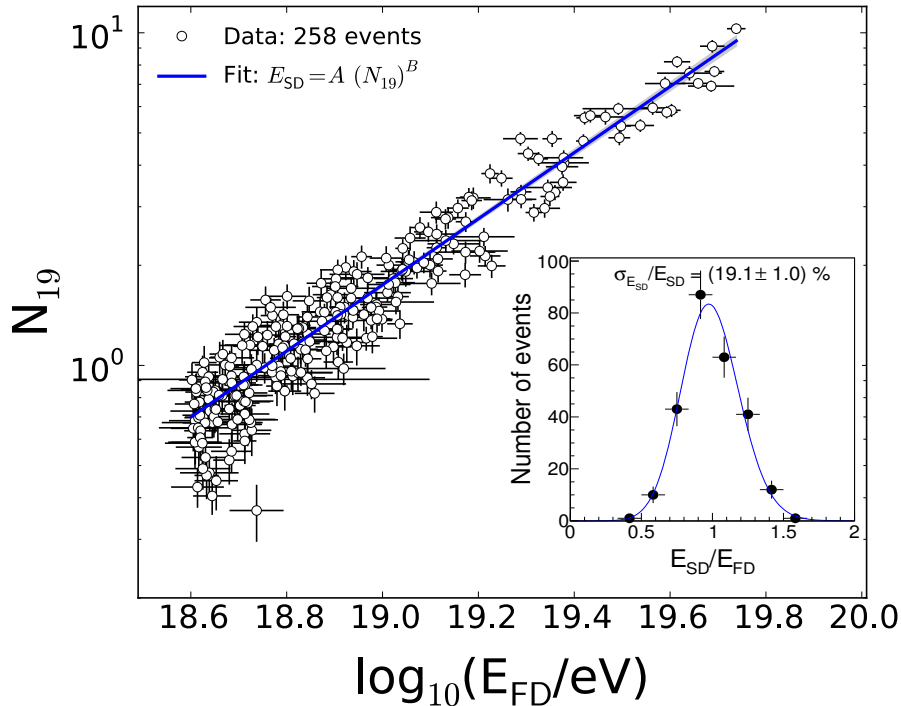
### 3 Spectrum

The shower size parameter,  $N_{19}$ , obtained from the reconstruction procedure of the SD data with  $\theta \geq 60^\circ$ , is used as the energy estimator. A high-quality subset of hybrid events is used to calibrate  $N_{19}$  with the calorimetric energy measured with the FD, as explained in [11]. The energy scale inferred from this subset is applied to all the inclined showers recorded with the SD.

Here we update the published SD energy scale for inclined showers [11] using data up to 31 December 2013, increasing the data sample by about 16% with respect to the one used in previous analyses [11, 15]. The resulting fit (based on a tailored maximum-likelihood method [28]) of a power-law to the 258 hybrid events is illustrated in figure 2. By inverting the fitted function, the energy estimate is given as  $E_{\text{SD}} = A(N_{19})^B$  and the corresponding calibration parameters are  $A = (5.708 \pm 0.086) \times 10^{18} \text{ eV}$  and  $B = 1.006 \pm 0.018$ . Uncertainties in the SD energy,  $E_{\text{SD}}$ , due to the calibration procedure range from 1.5% at  $10^{19} \text{ eV}$  to 4.5% at  $10^{20} \text{ eV}$ . Full details are given in [11]. In addition, there is an overall systematic uncertainty of 14% from the FD energy measurement [29] and an uncertainty of  $\sim 2\%$  attributed to the different angular distributions of the hybrid events and the full inclined data set used to calculate the spectrum [11]. By adding the uncertainties described above in quadrature, the total systematic uncertainty in  $E_{\text{SD}}$  ranges between 14% at  $10^{19} \text{ eV}$  and 17% at  $10^{20} \text{ eV}$ .

The resolution in the SD energy,  $E_{\text{SD}}$ , is computed from the distribution of the ratio of  $E_{\text{SD}}$  (after the calibration procedure) and the reconstructed FD hybrid energy,  $E_{\text{FD}}$ , assuming

<sup>1</sup>The unitary hexagonal cell is the region with vertices at the barycentre of each of the six triangles around the central station, with area given by  $D^2\sqrt{3}/2$  where  $D = 1.5 \text{ km}$  is the array spacing.



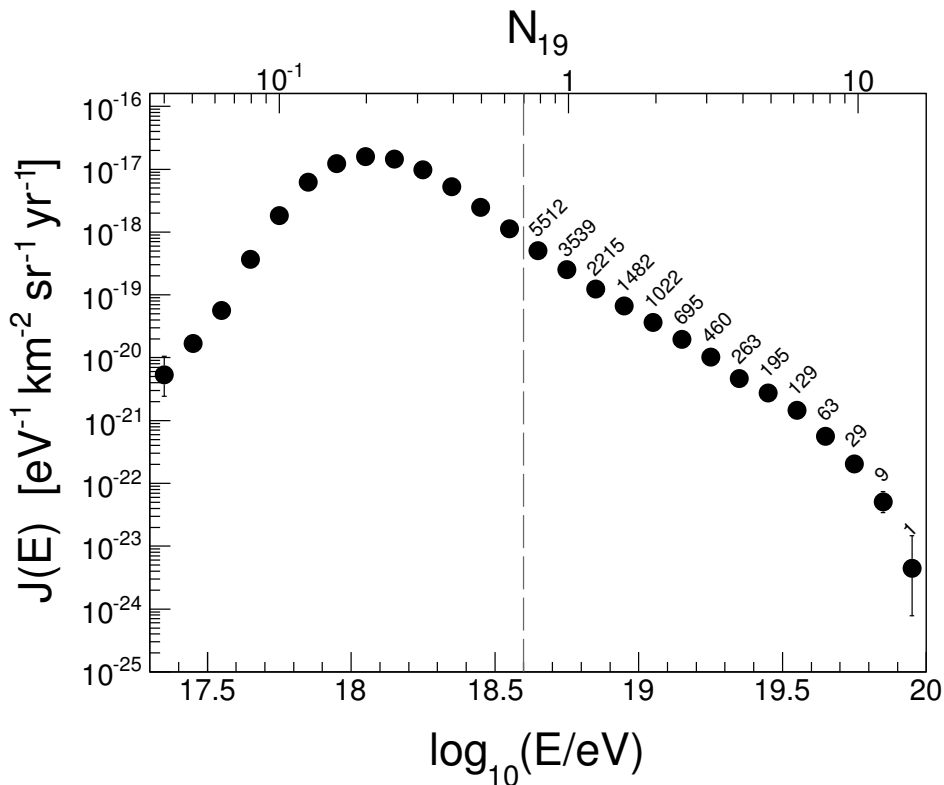
**Figure 2.** Correlation between the shower size parameter,  $N_{19}$ , and the reconstructed FD hybrid energy,  $E_{\text{FD}}$ , for the selected hybrid data with  $\theta \geq 60^\circ$  used in the fit. The solid line is the best fit of the power-law dependence  $E_{\text{SD}} = A (N_{19})^B$  to the data. The corresponding ratio distribution of the SD energy  $E_{\text{SD}}$  to the FD energy  $E_{\text{FD}}$  is shown in the inset.

a fixed FD energy resolution of 7.6% [29] (method based on [30]). The resulting average SD energy resolution is estimated to be  $(19 \pm 1)\%$  for the selected golden hybrid set (see inset in figure 2).

The selection (described in the previous section and in full in [11]) and the energy scale obtained here are applied to inclined events recorded by the SD in the time period between 1 January 2004 and 31 December 2013. The resulting data set consists of 254 686 events that fell on the active part of the array with zenith angles in the interval between  $60^\circ$  and  $80^\circ$ . To avoid large uncertainties due to the trigger and event selection efficiencies, only events having energies greater than  $4 \times 10^{18}$  eV are considered for the spectrum calculation, reducing the sample to 15 614 events.

The differential flux of cosmic rays at a certain energy  $E$ ,  $J(E)$ , is obtained by dividing the energy distribution of the cosmic rays by the accumulated exposure in the corresponding zenith-angle interval for the energies in the range of full trigger efficiency. Figure 3 shows this ratio for the selected events (also displayed as a function of the equivalent shower size  $N_{19}$ ). This is a raw distribution since effects of the finite resolution of the SD energy measurement have not yet been taken into account. Note that this figure also shows the ratio below  $4 \times 10^{18}$  eV where it is not expected that the flux will be reproduced accurately because of the energy dependence of the triggering efficiency (see figure 1).

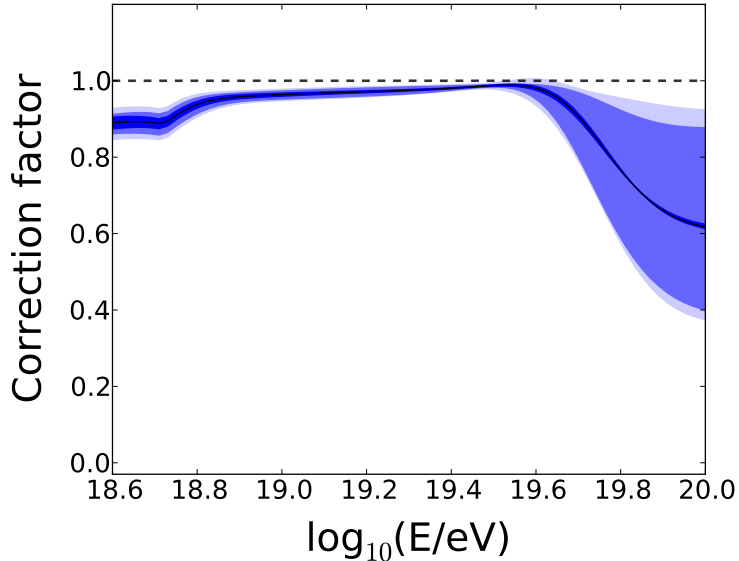
A correction must be applied to account for the effect of the resolution in the energy determination, responsible for a bin-to-bin event migration. The number of events in a given bin is contaminated by movements of reconstructed energies from the adjacent bins. For



**Figure 3.** Uncorrected energy spectrum of the cosmic rays derived from inclined events with zenith angles  $60^\circ \leq \theta \leq 80^\circ$  in terms of energy and shower size. Only statistical uncertainties are shown. The number of events in each of the bins above  $4 \times 10^{18}$  eV (vertical dashed line) is given above the points.

an energy spectrum which is steeply falling, upward fluctuations into a given bin are not completely compensated by other fluctuations from the other direction, and the net effect is an overestimate of the flux when this correction is not applied. Due to this, the measured spectrum is shifted towards higher energies with respect to the true spectrum. To correct for this, a forward-folding approach is applied. Monte Carlo simulations are used to determine the resolution of the SD energy estimator based on the shower size parameter,  $N_{19}$ , for different assumptions on the primary mass and hadronic interaction models. Then the average resolution is converted to the SD energy resolution using the same energy scale as obtained from the data. In addition, intrinsic fluctuations (also called shower-to-shower fluctuations) contribute to the bin migration. In this case, these fluctuations are modelled with a normal distribution that has a constant relative standard deviation,  $\sigma(N_{19})/N_{19}$ , and are estimated in the data-calibration procedure as explained in [11], resulting in  $\sigma(N_{19})/N_{19} = (14 \pm 1)\%$ . From the SD energy resolution and intrinsic fluctuations, a bin-to-bin migration matrix is derived. The matrix is then used to find a flux parameterisation that matches the measured data when forward-folded.

We assume a common parameterisation for the spectrum given a power law below the



**Figure 4.** Correction factor applied to the measured spectrum to account for the detector effects as a function of the cosmic-ray energy. The uncertainty due to the energy resolution is shown with the dark band, and that due to shower-to-shower fluctuations with the blue band. The total uncertainty, also including the uncertainty of the fit, is shown by the light band.

ankle and a power law plus a smoothly changing function above,

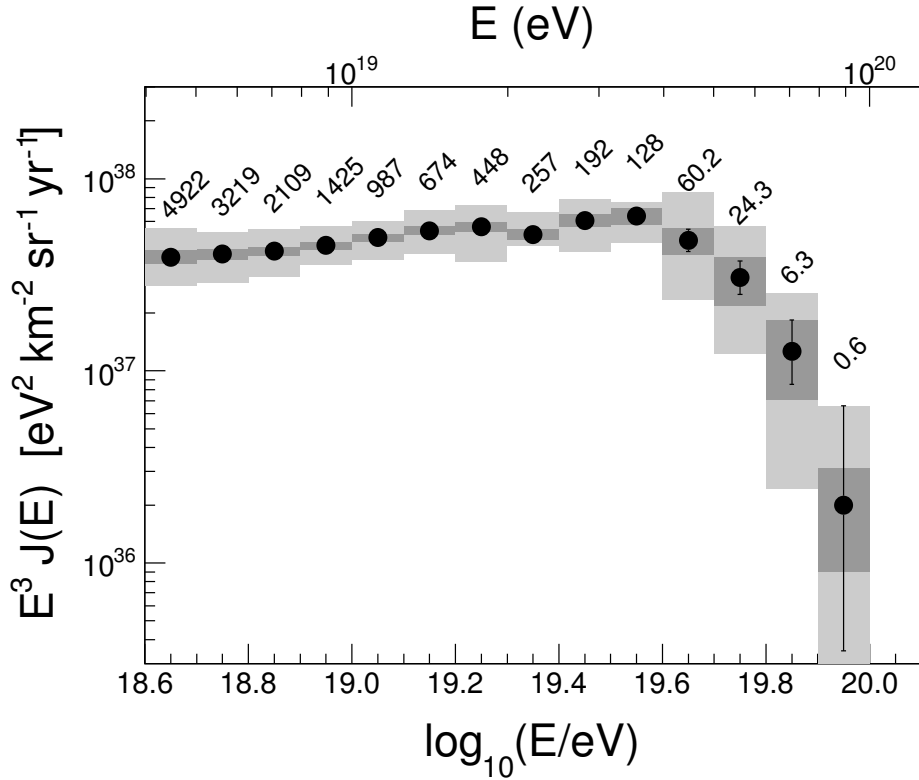
$$J(E) \propto E^{-\gamma_1} \quad ; E < E_{\text{ankle}}, \quad (3.1)$$

$$J(E) \propto E^{-\gamma_2} \left[ 1 + \left( \frac{E}{E_s} \right)^{\Delta\gamma} \right]^{-1} \quad ; E \geq E_{\text{ankle}}, \quad (3.2)$$

where  $E_s$  is the energy at which the flux falls to one-half of the value of the power-law extrapolation of the intermediate region and  $\Delta\gamma$  gives the increment of the spectral index beyond the suppression region<sup>2</sup>. This parameterisation was convolved with the migration matrix and the resulting flux was fitted to the measured spectrum, using a binned maximum-likelihood approach assuming Poisson statistics. As  $E_{\text{ankle}}$  is very close to the saturation energy for inclined showers, neither  $E_{\text{ankle}}$  nor  $\gamma_1$  can be reliably established from the data. These parameters are relevant for the unfolding of the lower-energy part of the spectrum. They were fixed to the values obtained in the spectrum reported in [8],  $\gamma_1 = 3.23 \pm 0.01 \pm 0.07$  (sys) and  $E_{\text{ankle}} = (5.25 \pm 0.12 \pm 0.24$  (sys))  $\times 10^{18}$  eV, while the other parameters were left free. The convolved flux is finally divided by the input flux to obtain the correction factors which are in turn applied to the measured binned spectrum.

The correction factor resulting from the fit of the assumed parameterisation is shown in figure 4. The uncertainty from the fit was obtained by propagating the covariance matrix of the fitted parameters into the correction function. A systematic uncertainty is attributed to possible variations of the shower-to-shower fluctuations, which can arise if the mass component changes and because of the changing depth  $X_{\text{max}}$  of the shower maximum over the energy range of interest. Although recent results [15] favour a transition from lighter to

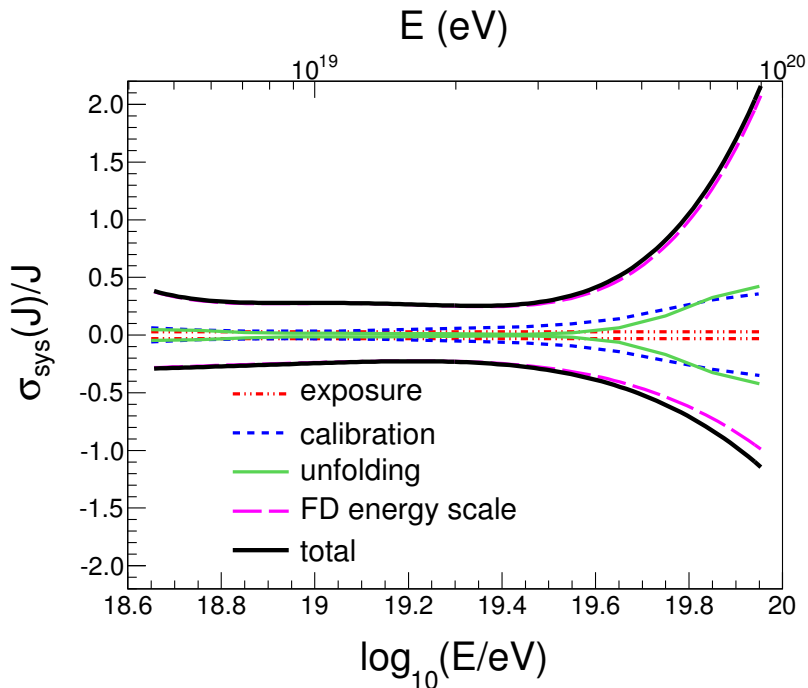
<sup>2</sup>Note that  $\Delta\gamma = 1/\ln(W_c)$  in the equivalent expression used in [7], where  $W_c$  defines the width of the transition region at the suppression.



**Figure 5.** Energy spectrum of the cosmic rays, corrected for energy resolution, derived from inclined data with zenith angles  $60^\circ \leq \theta \leq 80^\circ$ . The error bars represent statistical uncertainties. The light shaded boxes indicate the total systematic uncertainties. For illustration purposes, the systematic uncertainties excluding the uncertainty from the energy scale are also shown as darker boxes. The effective number of events, after correcting the flux for energy resolution, is given above the points.

heavier elements in the energy range considered, here we assume a conservative scenario where the relative fluctuations are allowed to vary between 4% (corresponding to a pure iron composition) and 21% (corresponding to a pure proton composition) over the full energy range. Finally, the propagated uncertainty in the average resolution of the energy estimator  $N_{19}$ , estimated to be on the order of 10%, was also included. In figure 4, in addition to the total uncertainty (light band), the last two uncertainty components are shown separately to illustrate that the main contribution is the systematic uncertainty due to variations of the shower-to-shower fluctuations.

The spectrum, corrected for energy resolution, is shown in figure 5. The error bars represent statistical uncertainties only. The flux is multiplied by  $E^3$  to better present its features, a flat region above  $4 \times 10^{18}$  eV up to the steepening at energies above about  $4 \times 10^{19}$  eV. The light shaded boxes indicate the total systematic uncertainties (less than  $\sim 40\%$  up to  $4 \times 10^{19}$  eV, and then increasing up to  $\sim 200\%$  for the highest energy bin), which include the uncertainty in the calibration parameters propagated to the flux, a global uncertainty derived from the SD exposure calculation (3%), the uncertainty arising from the unfolding process, and the global systematic uncertainty of the FD energy scale (14%) from the hybrid-calibration procedure. In figure 6 these separate contributions to the systematic uncertainties in the derived flux are shown as a function of the cosmic-ray energy.



**Figure 6.** Systematic uncertainties in the derived flux as a function of the cosmic-ray energy. For a description of the different sources of systematic uncertainty, see the text.

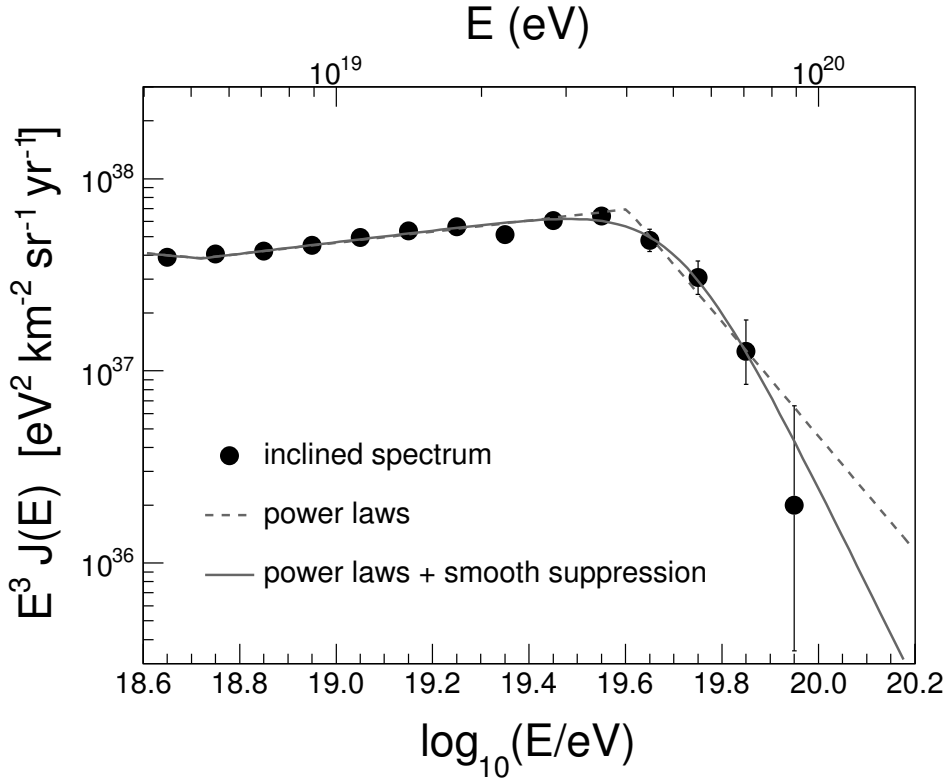
#### 4 Discussion

The characteristic features of the spectrum have been quantified by fitting the model given by eqs. (3.1) and (3.2), which assumes a spectrum with a sharp ankle and a smooth suppression at the highest energies, to the unfolded spectrum. The result of the best fit is shown as a solid line in figure 7. Another approach is to describe the spectrum with three power laws separated by two breaking points as illustrated by a dashed line in figure 7. The first model improves marginally the description of the abrupt change of slope observed at higher energies. The spectral parameters from the best fits to the data are given in table 1, quoting both statistical and systematic uncertainties.

Parameter	Power laws	Power laws + smooth suppression
$\gamma_2(E > E_{\text{ankle}})$	$2.71 \pm 0.02 \pm 0.1$ (sys)	$2.70 \pm 0.02 \pm 0.1$ (sys)
$E_{\text{break}}$	$(4.01 \pm 0.21_{-1.7}^{+1.0}) \times 10^{19}$ eV	
$\gamma_3(E > E_{\text{break}})$	$5.98 \pm 0.61_{-1.4}^{+0.9}$ (sys)	
$E_s$		$(5.12 \pm 0.25_{-1.2}^{+1.0}) \times 10^{19}$ eV
$\Delta\gamma$		$5.4 \pm 1.0_{-1.1}^{+2.1}$ (sys)
$\chi^2/\text{ndof}$	15.7/10	13.2/10

**Table 1.** Fitted parameters, with statistical and systematic uncertainties, parameterising the energy spectrum measured with the inclined events.

Note that, as explained above, the selected energy threshold of  $4 \times 10^{18}$  eV is, by coincidence, close to the value obtained for the ankle,  $(5.25 \pm 0.12) \times 10^{18}$  eV, in the combined



**Figure 7.** Energy spectrum of the cosmic rays, corrected for energy resolution, derived from inclined data fitted with simple power laws (dashed line) and with eqs. (3.1) and (3.2) (solid line). The systematic uncertainty on the energy scale is 14%.

analysis of hybrid events and SD events [8]. It is thus not possible to analyse the ankle transition properly. Nevertheless, the raw data do clearly display such a feature (see figure 3) which we do not analyse any further here due to the large uncertainty in the efficiency in this region (see figure 1). As a consequence, the  $\gamma_1$  and  $E_{\text{ankle}}$  parameters in equation (3.1) have been fixed to the values reported in [8].

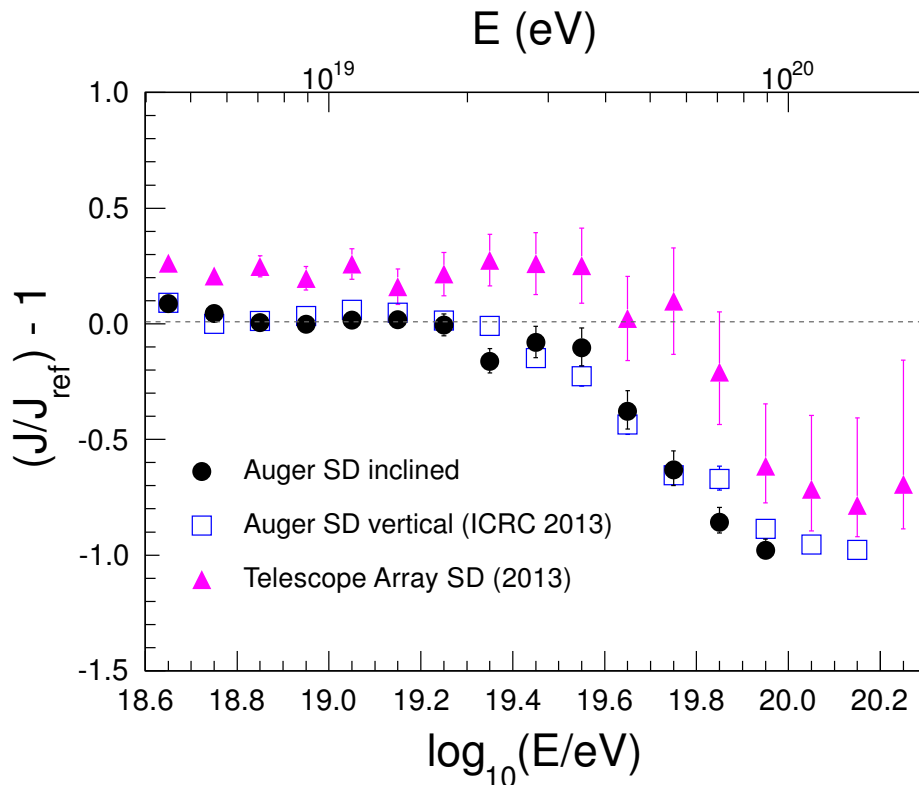
Both models consistently describe the “flat” region of the spectrum above the ankle up to the observed onset of the suppression at  $\sim 4 \times 10^{19}$  eV by a power law with a spectral index of  $\gamma_2 = 2.7$ . The spectral index after the steepening is less certain due to the low number of events and large systematic uncertainties. The significance of the suppression<sup>3</sup> is  $\sim 6.6 \sigma$  with 220.4 events expected above the break energy  $E_{\text{break}}$  while only 102 events were observed.

A different observable that characterises the suppression is the energy  $E_{1/2}$  at which the integral spectrum drops by a factor of two relative to the power-law extrapolation from lower energies, as suggested in [32]. Here, the integral spectrum was computed by integrating the parameterisation given by eqs. (3.1) and (3.2) and the parameters reported in table 1. The result yields  $E_{1/2} = (3.21 \pm 0.01 \pm 0.8(\text{sys})) \times 10^{19}$  eV, which is smaller than the value of  $\approx 5.3 \times 10^{19}$  eV predicted for the GZK energy cutoff of protons [32] (practically independent of the generation index of the assumed energy spectrum), with a difference at the level of  $2.6 \sigma$ . In [32] the assumption was made that the sources of ultra-high energy cosmic rays are

<sup>3</sup>Following the recipe given in [31], the null hypothesis that the power law with spectral index  $\gamma_2 = 2.71 \pm 0.02$  continues beyond the suppression point can be rejected due to the low probability  $(5^{+3}_{-2}) \times 10^{-11}$ .



uniformly distributed over the universe and are accelerators of protons. In reality, sources are discrete and in the GZK region the shape of the spectrum will be dominated by the actual distribution of sources around us. Further discussion of this point is given in [33]. Other scenarios for the high-energy suppression of the spectrum (e.g., [34–37]) attribute it to the limiting acceleration energy at the sources rather than to the GZK effect, providing a good description of the combined Auger energy spectrum as shown in [38].



**Figure 8.** Fractional difference between the energy spectrum of cosmic rays derived from SD data with  $\theta \geq 60^\circ$  recorded at the Pierre Auger Observatory and a reference spectrum with an index of 2.67. Residuals for spectra derived from Auger SD data with  $\theta < 60^\circ$  [8] and the Telescope Array SD data with  $\theta < 55^\circ$  [40] are also shown for comparison.

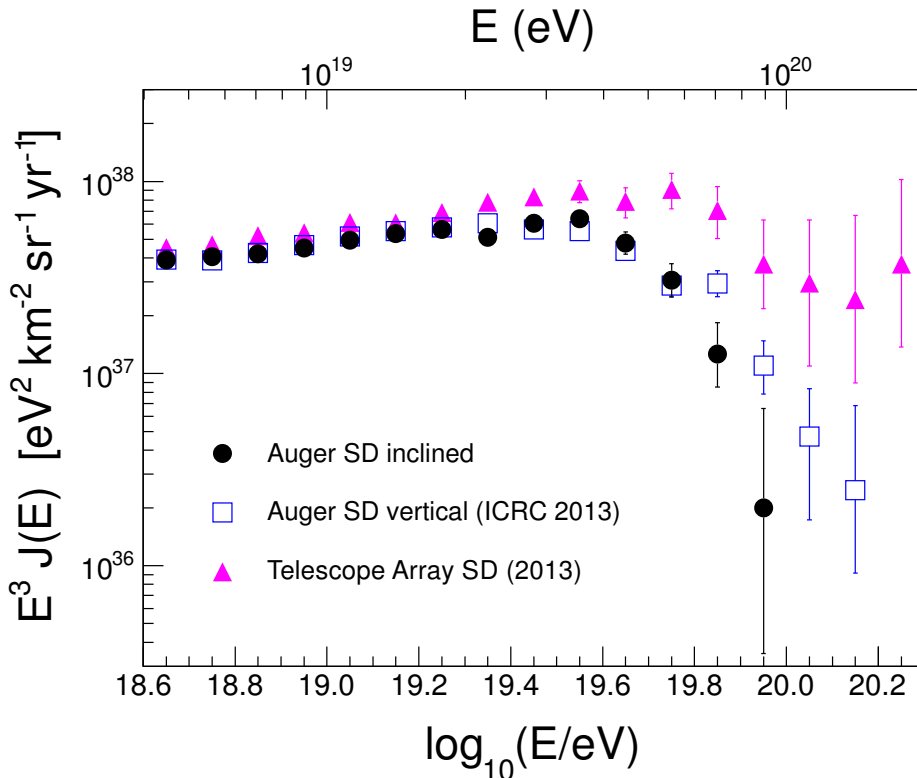
To compare the spectrum obtained here with other measurements, we have adopted the technique suggested in [39] in which the differential flux at each energy is compared with the expected differential flux from a reference spectrum. We choose as reference a spectrum with an index <sup>4</sup> of 2.67 fitted to the flux presented here (see figure 5) in the energy bin corresponding to  $\log_{10}(E/\text{eV}) = 18.95$  (bin width of 0.1), which contains over 1425 events. The reference spectrum is thus

$$J_{\text{exp}} = 2.52 \times 10^{31} E^{-2.67} \text{eV}^{-1} \text{km}^{-2} \text{sr}^{-1} \text{yr}^{-1}. \quad (4.1)$$

In figure 8 the spectrum obtained with inclined events is displayed as a fractional difference (also called the residual) with respect to the reference spectrum, in comparison to the residual for the spectrum obtained from data with zenith angles less than  $60^\circ$  [8]. The comparison shows that both spectra are in agreement within errors. We note that the last two

<sup>4</sup>The index of the reference spectrum has no physical significance, so its choice is quite arbitrary.

points are systematically below the corresponding measurement obtained for Auger events with zenith angles less than  $60^\circ$ . Also the point corresponding to  $\log_{10}(E/\text{eV}) = 19.35$  is below the vertical one. However, the differences are at the  $2\sigma$  level.



**Figure 9.** Compilation of the energy spectrum of cosmic rays derived from SD data recorded at the Pierre Auger Observatory with  $\theta \geq 60^\circ$  (circles) and  $\theta < 60^\circ$  (squares), and at the Telescope Array with  $\theta < 55^\circ$  (triangles).

Figure 8 also displays the spectrum obtained from SD events with zenith angles less than  $55^\circ$  recorded with the Telescope Array (TA) detector [40]. The comparison of the residuals for the three spectra (also illustrated in the form of  $J E^3$  in figure 9) shows that in the region between the ankle and the suppression the Auger spectra fit well due to our choice of reference spectrum, and the average of the residuals for TA is about +23%. The spectra determined by the Auger and TA Observatories are consistent in normalisation and shape within the systematic uncertainties in the energy scale quoted by the two collaborations [41]. However, differences are clearly seen in the high-energy region and are not understood thus far. Understanding the origin of this difference, whether from anisotropies at high energies, composition-related effects, experimental issues or any other reason, is of high priority in the efforts to understand the origin of the UHECRs. However the dedicated study of this discrepancy is beyond the scope of this work. Since 2012 there has been a collaborative effort between the Pierre Auger and Telescope Array Collaborations to investigate the level of agreement between the different measurements of the UHECR energy spectrum and to understand the sources of possible discrepancies, by examining the different measurement techniques and analysis methods employed by these groups. The latest results obtained by the energy spectrum working group can be found in [41].

## 5 Summary

The cosmic-ray spectrum has been obtained for energies exceeding  $4 \times 10^{18}$  eV using showers with zenith angles between  $60^\circ$  and  $80^\circ$  recorded with the surface detector of the Pierre Auger Observatory during the time period between 1 January 2004 and 31 December 2013. It has been shown that the SD array becomes fully efficient for inclined events above this energy. The results can be described by a power-law spectrum with spectral index 2.7 above  $5 \times 10^{18}$  eV and clearly indicate a steepening of the cosmic-ray spectrum above an energy around  $4 \times 10^{19}$  eV. These features and the normalisation of the spectrum are in agreement with previous measurements made with the Pierre Auger Observatory (using SD data and hybrid data with zenith angles less than  $60^\circ$ ) and also with the measurements of the Telescope Array.

The inclined data set is independent and complementary to the vertical data set and its reconstruction is performed using an independent method. These data provide a 29% increase in number of events over the previous event set. In addition to obtaining an independent measurement of the cosmic-ray spectrum reported here, the inclined data are being analysed to explore primary composition, to constrain the current models that attempt to describe the hadronic interactions at energies above  $4 \times 10^{18}$  eV ( $E_{\text{CM}} \approx 87$  TeV), and to improve the studies of the arrival directions of the cosmic rays by extending the accessible fraction of the sky to 85%.

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