Measurement of the cosmic ray energy spectrum above 10^{18} eV with the Pierre Auger Observatory

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Abstract: The flux of high energy cosmic rays above 10^{18} eV has been measured with the Pierre Auger Observatory using an unprecedented number of events. Here we present the energy spectrum derived using two data analysis methods. Above 3×10^{18} eV air showers measured with the array of water-Cherenkov detectors and an energy-independent aperture, calibrated by energy measurements made using fluorescence telescopes, are used to obtain a measurement of the energy spectrum. Using air showers detected with the fluorescence telescopes and at least one water-Cherenkov detector (so called hybrid events) a spectrum is derived for energies above 10^{18} eV. The two spectra are found to be consistent and a combined spectrum is derived. The impact of systematic uncertainties, and in particular the influence of the energy resolution, on the spectral shape is addressed.

Introduction

The Pierre Auger Observatory employs two independent techniques to observe extensive air showers created by ultra-high energy cosmic rays in the atmosphere. A ground array of more than 1600 water cherenkov detectors and a set of 24 fluorescence telescopes. Construction of the baseline design was completed in 2008. With stable data taking starting already in 2004, the worlds largest dataset of cosmic ray observations has been collected over the last years during the construction phase of the observatory. Here we report on an update with a substantial increases of the accumulated exposure of the energy spectrum measurements reported in [1] and [2].

The data of the surface detector array, calibrated with coincident measurements with the fluorescence detector, is due to its high statistics sensitive to spectral features at the highest energies. A flux suppression around $10^{19.5}$ eV has been established based on these measurements [1] and the HiRes experiment [3]. An extension to energies below the threshold of $10^{18.5}$ eV is possible with the use of hybrid observations, i.e. measurements of the fluorescence detectors in coincidence with at least one surface detector. Although statistically limited due to the duty-cycle of the fluorescence detectors of about 13%, these measurements allow to cover the energy range above 10^{18} eV and can therefore be used to determine the position and the shape of the ankle [4, 5, 6]. It has been realized over the last years that a precise measurement of this feature is crucial for the understanding of the underlying phenomena. Several phenomenological models with different predictions and explanations of the energy spectrum and the cosmic ray mass composition have been proposed. Constrains of these models implied by the spectrum presented here are discussed in conjuction with mass composition and arrival direction data in [7].

Surface detector data

The surface detector array of the Pierre Auger Observatory covers about 3000 km^2 of the argentinian Pampa Amarilla. Since its com-

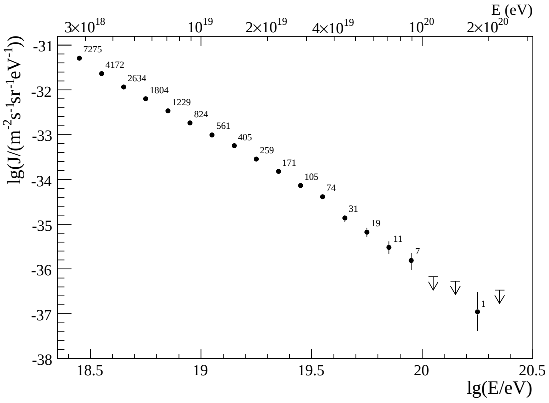

Figure 1: Energy spectrum derived from surface detector data calibrated with fluorescence measurements. **(to be updated with full statistics)**

pletion in 2008 the collected aperture increases each month by about 350 km^2 sr yr an amounts to 13.520 km^2 sr yr for the time period considered for this analysis (01/2004 - 02/2009). It is calculated by integrating the number of active unitary cells of the surface array over time. Detailed monitoring information about the status of each surface detector station with a time resolution of one second allow for the determination of the aperture with an uncertainty of 3 % [8].

The energy assignment of the recorded data is calibrated with a subset of high quality events observed by both the surface and the fluorescence detector after removing attenuation effects by means of a constant-intensity method [9]. The final systematic uncertainty of the energy calibration is $XX\%$ around $10^{18.5}$ eV. It increases to $XX\%$ above $10^{19.X}$ eV.

In addition also the energy resolution of the surface detector is energy dependent decreasing from $XX\%$ at $10^{18.5}$ eV to $XX\%$ above 10^{19} eV. Bin-to-bin migrations are therefore slightly modifying the spectral shape. Here we present an energy spectrum which has been corrected for these effects via a forward folding approach. Starting from a simple two-component model of the underlying spectrum an energy dependent correction to the reconstructed flux is derived from extensive MC simulations of the surface detector response. The resulting corrections are energy dependent and less than about 15%(??) over the full energy range. The derived energy spectrum is shown in Fig. 1. Combining the systematic uncertainties of the exposure and the energy calibration, the systematic uncertainties of the derive flux are $XX\%$ at the threshold of $10^{18.5}$ eV and increase to $XX\%$ above $10^{19.X}$ eV.

Fluorescence detector data

The fluorescence detector of the Pierre Auger Observatory comprises 24 telescopes grouped in 4 buildings around the surface array. Air shower observations of the fluorescence detector in coincidence with at least one surface detector allow for an independent measurement of the cosmic ray energy spectrum. Due to their lower energy threshold, these 'hybrid' events allow to extend the nominal range of the observatory to 10^{18} eV.

The exposure of the hybrid mode of the Pierre Auger Observatory has been derived from a novel detector Monte Carlo approach which reproduces the actual data conditions of the observatory including their time variability [10]. Based on the extensive monitoring of all detector components [11] a detailed description of the data taking efficiencies has been derived. The time dependent detector simulation is based on these efficiencies and uses the complete description of the atmospheric conditions obtained within the atmospheric monitoring program of the observatory [12]. As input to the detector simulation air showers are simulated with CONEX [13] based on the Sibyll 2.1 [14] and QGSJetII-0.3 [15] hadronic interaction models with a 50%−50% mixture of proton and iron primaries. Whereas the derived exposure is independent of the choice of the hadronic interaction model, a systematic uncertainty is induced by the unknown primary mass composition. It decreases from 6.5% at 10^{18} eV and becomes negligible above 10^{19} eV (see [10] for details).

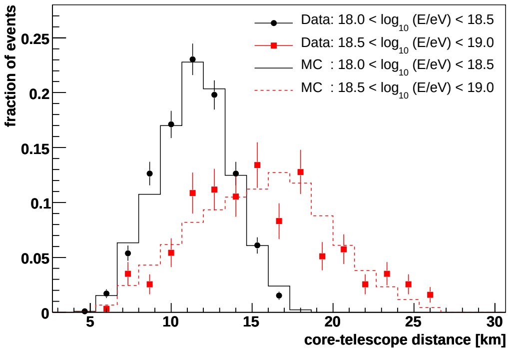

Figure 2: Comparison between hybrid data and the Monte Carlo simulations used for the determination of the hybrid exposure.

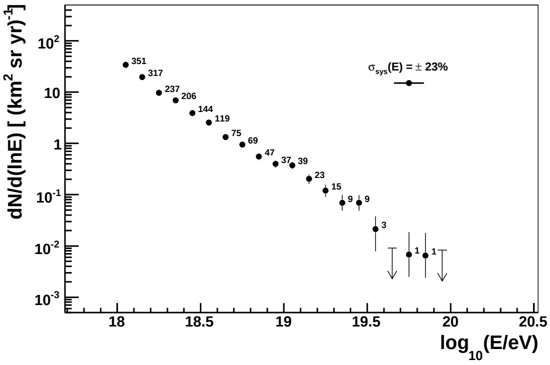

Figure 3: Energy spectrum derived from hybrid data. **(to be updated, including the correction factors)**

Extensive comparisons between simulations and cosmic ray data are performed on all reconstruction levels. An important example is the agreement between data and MC in the determination of the accessible fiducial volume shown in Fig. 2. Additional cross-checks involve artificial light sources like laser shots fired into the field of view of the fluorescence telescopes within the atmospheric monitoring program and the reproduction of events detected by the surface array with the developed simulation methods.

The energy spectrum derived from hybrid measurements recorded during the time period 12/2005 - 05/2008 is shown in Fig. 3. The systematic uncertainty is $XX\%$ at $10^{18.}$ eV and decreases to $XX\%$ above $10^{19.}$ eV

The combined energy spectrum

A single energy spectrum covering the full range from 10^{18} eV to above 10^{20} eV is derived by combining the two measurements discussed above. The combination procedure utilizes a maximum likelihood method which takes into account the systematic and statistical uncertainties of the two spectra. The applied procedure derives flux scale parameters to be applied to the individual spectra. These are $k_{\mathrm{SD}} = 1.0X$ ($k_{\mathrm{FD}} = 1.0X$) for the surface detector data and hybrid data respectively, showing the good agreement between the independent measurements. Propagating the individual contributions the systematic uncertainty of the combined flux is $XX\%$.

As the surface detector data is calibrated with hybrid events, it should be noted that both spectra share the same systematic uncertainty of the energy assignment. Its main contributions are the absolute fluorescence yield (14%) and the absolute calibration of the fluorescence photodetectors (9.5%). Including a reconstruction uncertainty of about 10% and uncertainties of the atmospheric parameters, an overall systematic uncertainty of 22% has been derived [16].

The combined energy spectrum is shown in Fig. 4. Its characteristic features are determined by fitting a simple powerlaw based functional form following E^{γ}. It includes a free break of the spectral index γ at an energy E_{ankle} to determine the position of the ankle. The flux suppression at ultra-high energies is described by an exponential cut-off at a free position E_{cut} with a width W_{cut}. The resulting fit is shown in Fig. 4 and the derived parameters (quoting only statistical uncertainties) are:

- $\gamma_1(E < E_{\mathrm{ankle}}) = -3.42 \pm 0.05$
- $\log(E_{\mathrm{ankle}}/\mathrm{eV}) = 18.58 \pm 0.01$

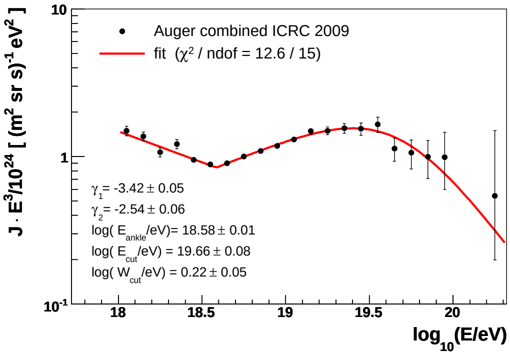

Figure 4: The combined energy spectrum.

- $\gamma_2(E > E_{\text{ankle}}) = -2.54 \pm 0.06$
- $\log(E_{\text{cut}}/\text{eV} = 19.66 \pm 0.08$
- $\log(W_{\text{cut}}/\text{eV} = 0.22 \pm 0.05$

Extrapolating a powerlaw fitted to the spectrum in the range $10^{18.5} - 10^{19.6}$ eV to higher energies, XX event would be expected above 10^{20} eV, whereas only XX are observed. A significance of the suppression of $X\sigma$ has been determined based on a TP-test [17] with minimum energy $E_{\text{ankle}} = 10^{18.58}$ ev corresponding to the position of the ankle.

Conclusions

We presented two independent measurements of the cosmic ray energy spectrum with the Pierre Auger Observatory. The combination of the high statistics surface detector data and the extension to lower energies using hybrid observations enables the precise measurement of both the ankle and the flux suppression at highest energies with unprecedented statistics. First comparisons with astrophysical models describing these features have been performed [7].

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