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Measurement of the ultra high energy cosmic ray energy spectrum with the Pierre Auger Observatory

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ABSTRACT

We report a measurement of the cosmic ray energy spectrum based on a large amount of data collected by the Pierre Auger Observatory. This measurement combines data from the fluorescence (FD) and surface (SD) detectors of the Observatory and does not rely on detailed numerical simulation or any assumption about the chemical composition. The energy calibration of the observables, which exploits the correlation of surface detector data with fluorescence measurements in hybrid events, is presented in detail. Besides presenting statistical uncertainties, we address the impact of systematic uncertainties. We also summarize the combined energy spectrum obtained when hybrid data are used to extend the spectrum to lower energies.

1. Introduction

The Pierre Auger Observatory [1] is designed to measure the extensive air showers produced by the highest energy cosmic rays ($E > 10^{18.5}$ eV) with the goal of discovering their origins and composition.

The observatory, located near Malargüe in the province of Mendoza in Argentina, consists of an array of 1660 water-Cherenkov Surface Detectors (SDs) [2] deployed on the ground over a triangular grid of 1.5 km spacing and covering an area of 3000 km^2. Each SD station is a polyethylene tank of cylindrical shape with size 10 $\text{m}^2 \times 1.2$ m, filled with purified water. The surface detector measures the front of the shower as it reaches the ground. The stations activated by the event record the particle density and their arrival time. Cherenkov light produced by charged particles of extensive air showers (EAS) in the water is detected by three 9 in. photomultipliers. Each station is autonomous with a battery and a solar panel. The signals are digitized using a Flash ADC system and the information is transmitted to the central data acquisition system by a microwave link.

The ground array is overlooked by 27 fluorescence telescopes, grouped in four sites, making up the fluorescence detector (FD) [3]. In each fluorescence telescope, the light is collected by a segmented spherical mirror of area 3.6 m × 3.6 m through a UV-transparent filter window and a ring-shape corrector lens. Each camera consists of 440 hexagonal photomultipliers, each with a field of view of 1.5°. The fluorescence detector (FD) observes the longitudinal development of the EAS in the atmosphere by detecting the fluorescence light emitted by de-excitation of nitrogen molecules excited by the charged particles of the shower in the air. The result is a measurement of the energy deposit as a function of the atmospheric depth, as in a calorimeter. This method can be used only when the sky is moonless and clear, and thus has roughly a 13% duty cycle. The surface detector (SD) has a 100% duty cycle. The hybrid events, which are air showers detected by both instruments, are very precisely measured [4] and provide the energy calibration tool. Using hybrid events, it is possible to relate the shower energy measured by the FD to the shower size parameter on the ground.

2. Analysis of surface detector data

The energy of a cosmic ray shower detected by the SD array is characterized by the parameter $S(1000)$, the signal expected in a detector at 1000 m from the axis, based on fitting the lateral distribution. The units of $S(1000)$ are VEM (Vertical Equivalent Muon), the signal produced by a relativistic muon passing vertically through the center of a water tank. A likelihood method is used to fit the lateral distribution function which then allows us to obtain the location of the shower axis, $S(1000)$, and the curvature

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of the shower front [5]. The selection criteria are such as to ensure the rejection of accidental triggers (physics trigger) and the events are well contained in the SD array (quality trigger). We require that all six nearest neighbors of the station with the highest signal be active. In this way, we guarantee that the core of the shower is contained inside the array and enough of the shower is sampled to make accurate measurement of $S(1000)$. The present data set was taken from 1 January 2004 through 31 September 2010. To ensure an excellent data quality, we remove periods with problems due to failures in data acquisition, due to lightning and hardware difficulties. We select events with zenith angle less than 60° and with reconstructed energy above 3 EeV. For this analysis, the array is fully efficient and the acceptance at any time is determined by the geometric aperture of the array [6]. The integrated exposure is about 21 000 km^2 sr yr.

For a given energy the value of $S(1000)$ decreases with zenith angle, θ, due to attenuation of the shower particles and geometrical effects. Assuming an isotropic flux for the whole energy range considered, i.e. that the intensity distribution is uniform when binned in $\cos^2(\theta)$, we extract the shape of the attenuation curve from the data. The fitted attenuation curve, $CIC(\theta)=1+ax+bx^2$, is a quadratic function of $x=\cos^2\theta-\cos^2 38^\circ$ as displayed in Fig. 1 for a particular constant intensity cut, with $a=0.87\pm0.04$ and $b=1.49\pm0.20$. Since the median of the zenithal distribution (between 0° and 60°) is $\langle\theta\rangle\approx 38^\circ$ we take this angle as reference and convert $S(1000)$ into S_{38° by $S_{38^\circ}\equiv S(1000)/CIC(\theta)$. It may be regarded as the signal $S(1000)$ the shower would have produced if it had arrived at $\theta=38^\circ$ [7]. The reconstruction accuracy of the parameter $S(1000)$, $\sigma_{S(1000)}$, is estimated from: the statistical uncertainty due to the finite size of the detector and the limited dynamic range of the signal detection, the systematic uncertainty due to the assumptions of the shape of the lateral distribution and finally due to the shower-to-shower fluctuations [8]. These uncertainties are taken into account in inferring S_{38° and $\sigma_{S_{38^\circ}}$.

To infer the energy we have to establish the relation between S_{38° and the calorimetric energy measurement, E_{FD}. A set of hybrid events of high quality are selected based on the criteria reported in Ref. [4] but without applying a cut on the field of view, which appears to have a negligible effect for the topic addressed here. A correction to account for the energy carried away by high energy muons and neutrinos, the so-called invisible energy, depends slightly on mass and hadronic model. The applied correction is based on the average for proton and iron showers simulated with the QGSJet model and sums up to about 10% and its systematic uncertainty contributes 4% to the total uncertainty in FD energy [9]. The selected hybrid events were used to calibrate the SD energy. For each hybrid event, with measured FD energy E_{FD}, the SD energy estimator S_{38° was determined from the measured $S(1000)$ by using the constant intensity method described above. For each event, the uncertainty in S_{38° is estimated by summing in quadrature three contributions: the uncertainty in the constant intensity parametrization, $\sigma_{S_{38^\circ}}$ (CIC) , the angular accuracy of the event, $\sigma_{\cos\theta}$, and the uncertainty in the measured $S(1000)$, $\sigma_{S(1000)}$. The fluorescence yield used to estimate the energy E_{FD} is taken from Ref. [10]. An uncertainty in the FD energy, $\sigma_{E_{FD}}$, was also assigned to each event. Several sources were considered. The uncertainty in the hybrid shower geometry, the statistical uncertainty in the Gaisser–Hillas fit to the profile of the energy deposits and the statistical uncertainty in the invisible energy correction were fully propagated. The uncertainty in the measurement of the vertical aerosol optical depth profile [11] was also propagated to the FD energy on an event-by-event basis. These individual contributions were considered to be uncorrelated, and were thus combined in quadrature to obtain $\sigma_{E_{FD}}$. The data appear to be well described by a relation $E_{FD}=aS^b_{38^\circ}$ (see Fig. 2).The best fit yields $a=[1.68\pm0.05]\times10^{17}$ eV and $b=1.035\pm0.009$ with a reduced χ^2 of 1.1. The relative statistical uncertainty in the derived SD energy, E_{SD}/E_{SD}, is rather small, e.g. of the order of 5% at 10^{20} eV. See more details in Ref. [7].

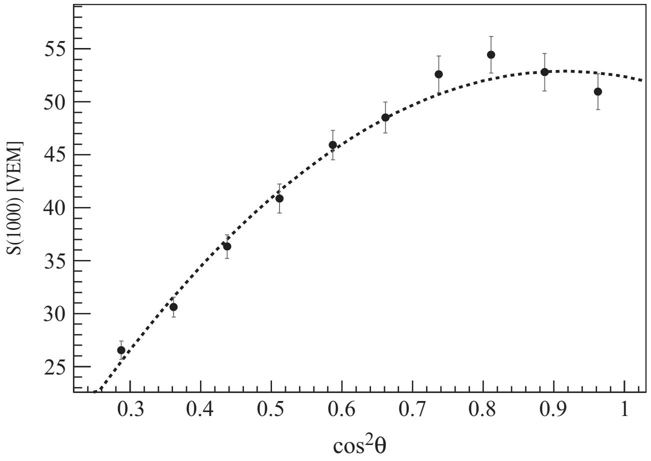

Fig. 1. Derived attenuation curve, $CIC(\theta)$, fitted with a quadratic function.

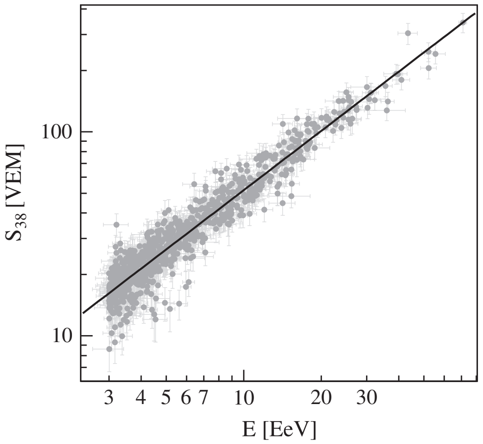

Fig. 2. Correlation between lg E_{FD} and lg S_{38° for the 839 hybrid events used in the fit. The full line is the best fit to the data.

3. The spectrum

The hybrid spectrum is measured with hybrid events and has been determined using data collected between November 2005 and September 2010. The exposure of the hybrid detector, see Fig. 3, has been calculated using time-dependent Monte Carlo simulations taking into account the changing configurations of FD and SD, as well as atmospheric conditions [12,13]. Only events that satisfy high quality criteria are selected and provide an energy resolution of about 10%. The total systematic uncertainty on the obtained exposure is quoted as 10% at 10^{18} eV and 6% at 10^{19} eV. A total of 3660 good hybrid events have been selected and have been used for the measurement of the energy spectrum above an energy of 10^{18} eV [4].

The exposure for the SD spectrum, see Fig. 3, was calculated by integrating the number of active stations of the surface array over time and it is calculated above 3×10^{18} eV where the SD acceptance is saturated independent of the primary mass. It is 21 000 km^2 sr yr, as calculated between January 2004 and September 2010, and is known with an uncertainty of about 3%.

In top panel of Fig. 4, we show the energy spectrum from SD data using showers at zenith angles below 60°, and in the bottom panel of the same figure the spectrum derived from the hybrid data set (fluorescence events in coincidence with at least one SD