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Measurement of the UHECR spectrum above 10^{19} eV at the Pierre Auger Observatory using showers with zenith angles greater than 60°

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Abstract: We report a measurement of the cosmic ray energy spectrum obtained using the inclined events detected with the Pierre Auger Observatory. Showers with zenith angles between 60° and 80° recorded in the period between 1 January 2004 and 28 February 2007 are analysed. Showers are first reconstructed in arrival direction and then fitted to density maps of the muon numbers obtained from 10^{19}eV simulated proton showers for different arrival directions, in order to obtain the core position and an overall normalisation factor N_{19} which is used as an energy estimator. The parameter N_{19} is shown to be correlated with the shower energy measured with the fluorescence technique for a sub-sample of good quality hybrid showers. This correlation, measured with hybrid events, is then used to determine the energy of all the showers.

Introduction

Inclined showers are detected regularly with the Pierre Auger Observatory. They are of interest because they enhance both the exposure of the detector and its sky coverage. Showers induced by hadronic nuclei with zenith angles greater than 60° are mainly composed of muons at ground level and their detection provides complementary information, relevant for composition and hadronic model studies. In addition inclined events constitute a background for the detection of neutrino-induced showers.

The Pierre Auger Observatory combines the surface and fluorescence techniques to study high-energy cosmic ray showers. The surface detector (SD), described in [1], uses 1.2 m deep water-Cherenkov tanks that provide enhanced sensitivity to muons and make the Auger Observatory suitable for studying inclined showers. Inclined events are reconstructed using a special analysis procedure to account for the muons deviating in the geomagnetic field [2]. The energy assignment is performed using an estimator that is calibrated with a subset of events (hybrid) which are also detected with the fluorescence detector (FD), in a manner similar to what is done for showers below 60°. The energy spectrum of cosmic ray above 6.3 EeV and with zenith angles between 60° and 80° as measured with the Pierre Auger Observatory is presented for the first time and shown to be consistent with that measured for events below 60°.

Analysis and results

The event reconstruction is essentially a two-fold process. First the arrival direction of the shower is reconstructed using the measured start time of the signals in the tanks. Then the core and the size of the shower are determined using the relative distributions of the muon number densities at ground level, "muon maps", which are obtained from simulation [2]. The muons entering the tank are converted to signal by convoluting with the tank response which has been simulated with the GEANT4 package, accounting for the different relevant processes. Signal probability distributions are evaluated and the best core position and N_{19}, the normalization factor of the muon map, are obtained using a maximum likelihood method. N_{19} can be used as an energy estimator and its relation to shower energy is determined experimentally using inclined hybrid events.

Before comparing the measured signal to the muon maps, the electromagnetic component of the signal is subtracted. Close to 60° an electromagnetic contribution from the main showering process, arising from neutral pions, can be expected, particularly close to the shower axis. At very high zenith angles the only electromagnetic contribution arises from the muons themselves, mainly through muon decay in flight, and is of order 15%. These contributions have been calculated using simulations of protons with AIRES at different energies and zenith angles (proton primaries, being more penetrating, have the largest electromagnetic contribution). The fraction of electromagnetic signal to the total has been parametrised as a function of zenith angle and distance to the core.

The reconstructed N_{19} values are calibrated using the sub-sample of events which are recorded simultaneously by the FD. For these hybrid events a direct measurement of the energy released in the atmosphere by the electromagnetic component of the shower is available. The yield used to estimate the FD energy is taken from [3]. The events used are selected according to a set of standard quality cuts in the FD reconstruction [4], with minor adjustments optimised for this analysis. The requirement that the shower maximum is well contained in the field of view of the FD strongly constrains the geometry of inclined events and there are no events above 75°. The correlation between FD energies and N_{19} values is shown in figure 1. The calibration curve is obtained by a linear fit to the data points in this logarithmic plot, in the form $N_{19} = 10^{\alpha} E_{FD}^{\beta}$, that yields best fit values of $\alpha = -0.77 \pm 0.06$ and $\beta = 0.96 \pm 0.05$.

A high-level trigger (T5) is defined for the SD events; it has a two-fold purpose, to assure the quality of the reconstruction avoiding events falling close to the border of the array and to allow a simple geometrical calculation of the exposure. The T5 definition requires that the tank closest to the reconstructed core is surrounded by an hexagonal ring of working stations. With this definition, the aperture is calculated, for a given array configuration, by counting the number of T5 hexagons and integrating in solid angle. The aperture for events with zenith angles exceeding 80° only represents about 12% of that above 60° and these events are discarded because as the zenith angle increases the uncertainty associated with the angular reconstruction rises. In addition, for zenith angles above 80° the triggering efficiency decreases rapidly. The total exposure is determined by integrating the instantaneous aperture weighted by the detection efficiency over the different array configurations during the period of time. The detection efficiency has been calculated using the muon maps. For values of $N_{19} > 1$ the efficiency integrated over the solid angle range exceeds 98%. Only events with $N_{19} > 1$ ($E \sim 6.3$ EeV) are considered for the present analysis. In figure 2 the $\sin^2\theta$-distribution is shown to be flat for $N_{19} > 1$ consistent with the result deduced from simulation.

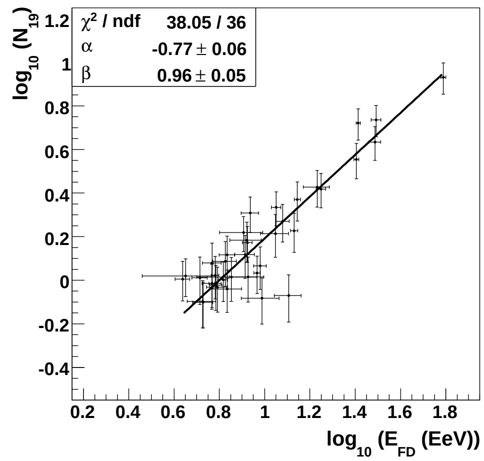

Figure 1: Correlation between FD energies and N_{19} in double logarithmic scale. The calibration curve, obtained by a linear fit to the data points, is shown superimposed.

The cosmic ray energy spectrum in the angular range between 60° and 80° as measured by the Pierre Auger observatory between 1 January 2004 and 28 February 2007 is shown in figure 3. A total of 734 events are used to build the spectrum and the integrated exposure in the period amounts to 1510 $\mathrm{km}^2\mathrm{sr\ year}$, i.e. 29% of the exposure for events below 60° [5].

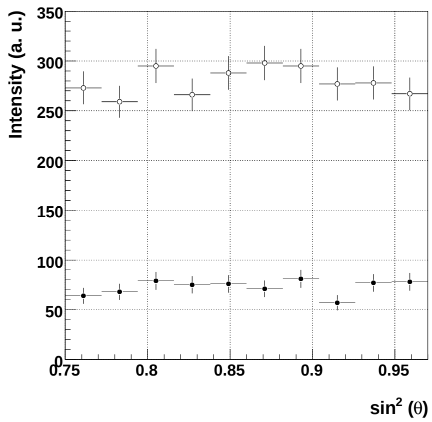

Figure 2: Distribution of $\sin^2\theta$ for T5 events and two different values of N_{19} ($1.0 > N_{19} > 0.4$, open circles; $N_{19} > 1.0$, full circles). The distribution flattens for higher N_{19} as the detector reaches full efficiency.

Discussion

The reconstruction of inclined showers is a relatively new challenge. Some of the uncertainties in the reconstruction are avoided by using the FD energy calibration as for the analysis for showers below 60°. There are still a number of systematic uncertainties which need to be discussed in some detail. Several test and cross-checks have been performed to ensure the validity of the results, as discussed below.

The inclined shower reconstruction uses simulated muon maps. For a given arrival direction the shape of the muon distributions is quite insensitive to the energy, to the composition and to the hadronic model used in the simulation [6]. Differences can be quantified by an overall normalization. The procedure to obtain the energy by correlating N_{19} with the FD energy takes care of a great part of the systematic normalization changes. The maps implicitly account for the attenuation of the muon content due to the different amounts of matter traversed for the different zenith angles. The study of the $\sin^2\theta$ distribution (figure 2) suggests that this effect is below the current level of statistical uncertainties. There is a systematic uncertainty which stems from the angular uncertainty, of order 1°, in the reconstruction which translates directly to a

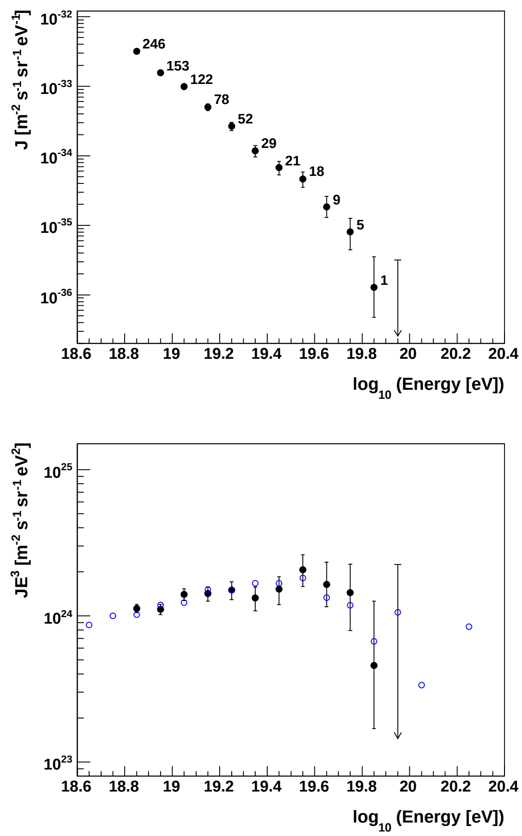

Figure 3: Upper panel, inclined event energy spectrum (statistical errors or 95% CL, number of events in each bin indicated) . Lower panel, spectrum multplied by E^3. The spectrum obtained for events below 60° [5] is superimposed (blue open circles).

change of N_{19}. The corresponding uncertainty in N_{19} increases as the zenith angle rises and has a maximum value of 12% at $80°$.

The reconstruction process depends on the models and on composition, mainly through the electromagnetic component, introducing possibly the largest systematic uncertainty. The effect has been explored by changing the fraction of electromagnetic correction applied to the data by an overall normalization factor that ranges between 1.5 and 0.5. The net effect on average is an overall change in N_{19} for showers of zenith angle above $65°$ that is independent of zenith angle and energy. Such sys-

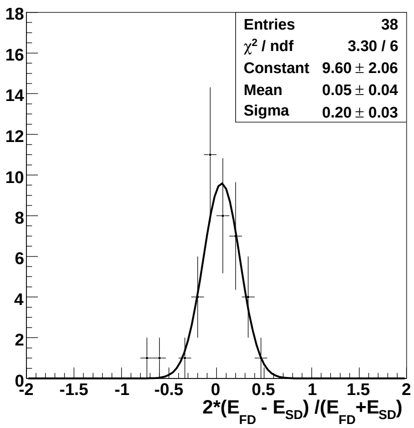

Figure 4: Relative difference between FD energies and calibrated energies for the events in the calibration plot.

tematic change would be on average reabsorbed in the energy correlation plot. Below 65° the average normalization obtained in the reconstruction shifts by less than 7%. We tentatively assign this value to the systematic error associated to the electromagnetic part.

The calibration curve is another possible source of systematic uncertainty. Effects due to the cuts applied to assure the quality of the reconstruction of the FD events have been carefully evaluated and are at the level of 10%, within the statistical significance of the calibration curve. Also, currently only 38 events are available.

The uncertainty in the measurements of the aperture is $\sim 3\%$, negligible in view of other uncertainties. The effect of the quality trigger has been evaluated using well contained showers found in the data and randomly repositioning them in the real array. The distribution of the N_{19} values obtained after the reconstruction of the events has an RMS value of 7%. The fraction of events that are misreconstructed to be outside the array is 4%.

At the moment the main source of systematic uncertainty in the analysis comes directly form the uncertainty in the FD energy scale, that is quoted at 22% level, dominated by a $14\ \%$ uncertainty in the fluorescence yield measurement, 11% in the detector calibration and 10% in the reconstruction method [7].

The hybrid events can be used also to test the SD reconstruction. The distribution of the difference between the SD and the FD hybrid-reconstructed energies normalised to the FD energy is shown in figure 4. The RMS fractional deviation is $(20 \pm 3)\%$. This is consistent with the combination of statistical uncertainties, uncorrelated FD systematics uncertainties, shower to shower fluctuations and the systematic uncertainties estimated for this analysis.

The spectrum observed is in good agreement with the SD spectrum for events below 60°. The comparison between the two spectra has implications for composition and/or hadronic models. This is presently under study.

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