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A description of some ultra high energy cosmic rays observed with the Pierre Auger Observatory

The Pierre Auger Collaboration
Presenter: J. Matthews (matthews@phys.lsu.edu) usa-ave-pernas-M-abs1-he14-oral

A discussion is given of the highest energy events so far recorded by the Pierre Auger Observatory. We present these to illustrate the quality of the information that they contain. The surface detectors are used to measure a rich set of parameters that will eventually help characterise the mass of the incoming primary particle.

1. Introduction

The Auger Southern Observatory is being used to explore the highest energies of the cosmic ray spectrum (>10 EeV). The surface detector (SD), with an accumulated acceptance larger than 1600 km^2 sr y, has already recorded a large number of high energy events. The fluorescence detector (FD) duty cycle is $\sim$ 14% of the SD. All the FD events presented here are recorded also by the SD ("hybrid" events). We also will restrict our discussion to events within 60^0 of zenith.

The FD measures the longitudinal development of showers, as the fluorescence light is proportional to the energy dissipated by the shower particles. This technique provides a calorimetric measurement of the energy of the primary particle and determines the position of the shower maximum ($\mathrm{X_{max}}$). The SD is an array of water-Cherenkov stations on a hexagonal grid of 1500 m spacing. S(1000), the signal at 1000 m from the shower axis, is a quantity measured accurately by the SD. Traditionally this measurement has been linked to primary energy by making assumptions about the unknown primary mass and about the hadronic interactions important for shower development. The hybrid nature of the Auger Observatory allows us to overcome these inherent uncertainties through a cross-calibration of the S(1000) measurement with a calorimetric measurement with the FD.

2. Highest energy events recorded with the Surface Detector

The event reconstruction procedure is described elsewhere [2, 3]. The core location is obtained by fitting the station signal size to the expected lateral distribution function (LDF). The LDF used in this work is:

$$S(r) = A\left(\frac{r}{r_s}\right)^{-\beta}\left(1+\frac{r}{r_s}\right)^{-\beta},$$

with β and A are free parameters, $r_s = 700$ m and r is the distance of a station to the shower axis. The experimental determination of the LDF is discussed in [4].

In every event there is an optimum distance, r_{opt} , at which uncertainties in β induce the smallest fluctuations on the reconstructed signal S(r_{opt}). The fit initially takes β as a free parameter, but if that does not result in $800 < r_{opt} < 1200$ m, then the event is reconstructed using β equal to the average at this zenith angle and including the small energy dependence of β that is observed.

The uncertainty assigned to S(1000) is given by a likelihood fit. A systematic uncertainty arises since β differs from shower-to-shower because of the stochastic nature of shower development[5]. To estimate this uncertainty, S(1000) is refitted using a range of β values drawn from a Gaussian distribution having a 10% rms spread around the average β, consistent with what has been found from other studies[5]. The systematic uncertainty in S(1000) is based on outcomes from the 1 σ fluctuation of β.

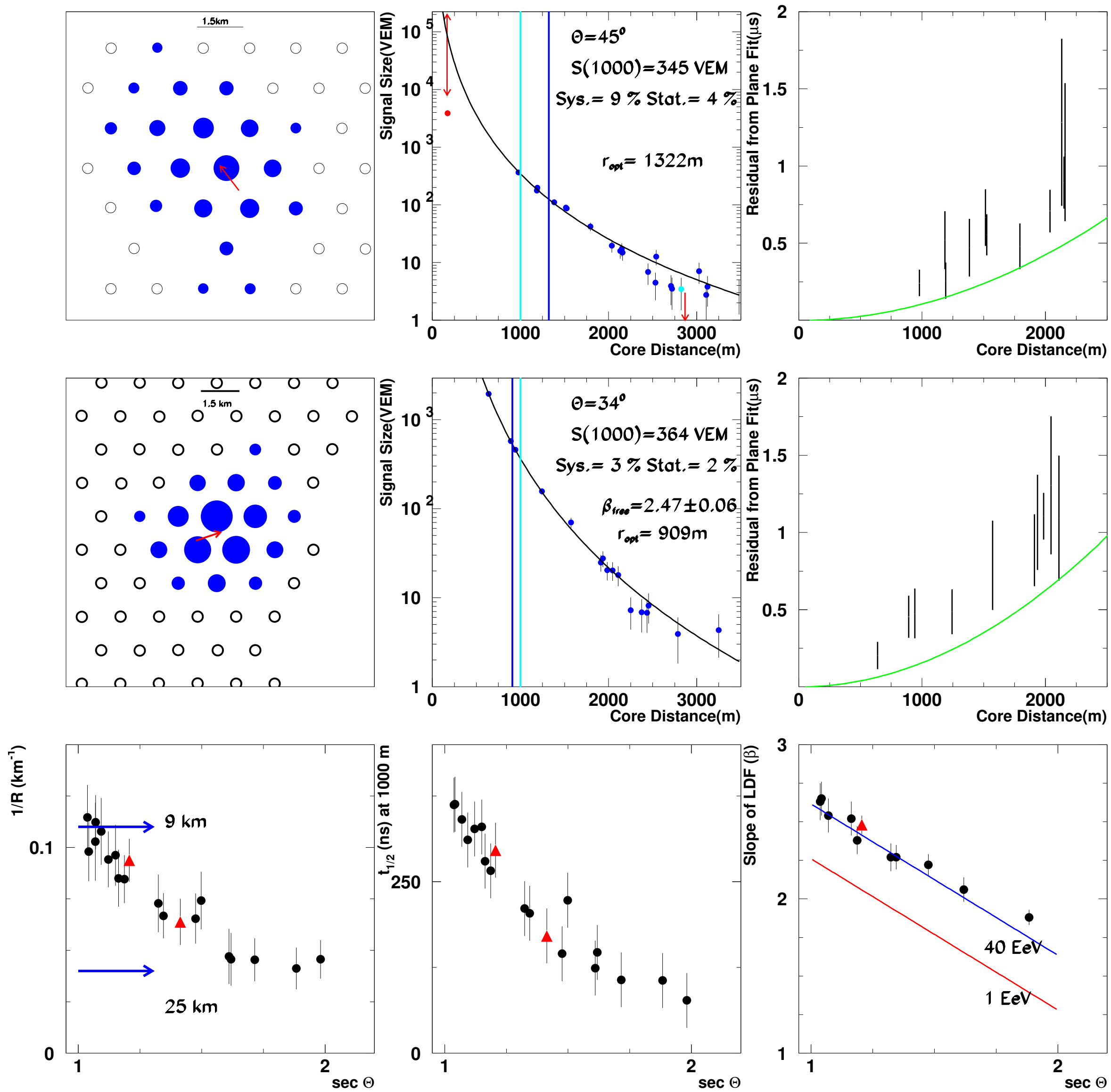

Figure 1. **Top**: The highest energy SD event (86 EeV). At left, triggered stations (blue). The arrow shows the fitted direction. Center, the best-fit LDF. Arrows indicate values used in the likelihood fit from a saturated station and from an untriggered one. Vertical lines denote r_{opt} and $r = 1$ km. At right, timing residuals, where the vertical length indicates shower front thickness ($t_{1/2}$, the time interval for 10% to 50% signal), and the curve shows the fitted start times. **Middle:** The second highest energy event recorded by SD (79 EeV). **Bottom:** Properties of the 20 most energetic events in the energy spectrum[1]. The curvature, shower front thickness at 1 km and β (when fitted) are shown as a function of zenith angle. Lines are the averages for the data at two energies. The (red) triangles correspond to the two highest energy events.

Event Id	θ	S(1000)	Multiplicity	r_{opt}	β	E(EeV)
1096757	45.1 ± 0.2	$344 \pm 15 \pm 33$	21	1322	—	86 ± 9
1225537	34.4 ± 0.2	$364 \pm 10 \pm 13$	14	909	2.48 ± 0.06	79 ± 4
787469	59.7 ± 0.2	$204 \pm 8 \pm 11$	31	1173	2.03 ± 0.06	76 ± 5
762238	47.3 ± 0.2	$248 \pm 11 \pm 12$	18	1135	2.22 ± 0.07	64 ± 4
1102721	23.8 ± 0.2	$318 \pm 22 \pm 52$	12	1467	—	63 ± 11
1233429	54.3 ± 0.2	$201 \pm 9 \pm 16$	21	1261	—	63 ± 6
1018639	26.9 ± 0.2	$294 \pm 19 \pm 26$	10	1196	2.93 ± 0.13	59 ± 6
1264145	16.3 ± 0.2	$289 \pm 12 \pm 11$	11	910	2.65 ± 0.11	56 ± 3
1263529	20.7 ± 0.2	$264 \pm 20 \pm 34$	7	1470	—	51 ± 8
634746	51.6 ± 0.2	$174 \pm 9 \pm 12$	14	1203	—	48 ± 4

Table 1. The 10 highest energy events recorded by the Surface Detector.

Some details of the 10 highest energy events are shown in Table 1. The first uncertainty given for S(1000) is statistical, the second is systematic. Energies are computed as described in [1]. The uncertainty for E is derived from the two uncertainties in S(1000) by adding them in quadrature.

Features of the 20 highest energy SD events are shown in Fig. 1. The trends with zenith angle of curvature, the risetime[6] at 1 km and β are qualitatively sensible and there is no evidence to suggest that any of these events has anomalous properties.

3. Highest energy events recorded with the Fluorescence Detector

As in the case of the surface detector we describe the reconstruction of hybrid events only briefly[3]. The shower detector plane (SDP, defined by the shower axis and the telescope position) is obtained from the pixel configuration in the camera. The angle of the shower axis in the SDP (χ_0) and the distance to the shower axis (R_p) are obtained by fitting the combined timing information of the SD stations and the pixels to a spot moving at the speed of light. Once the geometry is fixed, the profile is fitted using a χ^2 minimimization. The shower profile is characterised by a Gaisser-Hillas function with $\mathrm{X}_{\mathrm{max}}$ and the energy deposited in the atmosphere at shower maximum as free parameters.

There are 5 hybrid events above 10 EeV that survive the following cuts: $\theta < 60\ ^0$, $\mathrm{X}_{\mathrm{max}}$within the field of view, less than 50% Cherenkov contamination, a track larger than 250 g cm^{-2}, hybrid core less than 800 m away from the station with the highest signal, and core fully contained within the SD array. An example is shown in Fig. 2 (top). The energy of this event is 10.2 EeV and the reconstructed $\mathrm{X}_{\mathrm{max}} = (774 \pm 20)\mathrm{g\ cm}^{-2}$.

The highest energy event recorded so far was not included in Table 1, nor was it used in the energy spectrum, because it did not meet the acceptance criteria[1]. The core fell outside of the boundary of the SD at that time. It was, however, well fitted by the FD. Some details of this event are in shown in Fig.2 (bottom). There were five SD signals, the largest about 1600 m from the core determined by the FD fit. The hybrid and monocular FD reconstructions for this event are in good agreement.

Analysis of the longitudinal profile, assuming an aerosol-free (Rayleigh) atmosphere, leads to a lower limit of 140 EeV for the energy. Assuming more typical atmospheric clarity (atmospheric monitoring was not yet routine at the time of this event), yields an energy of approximately 200 EeV. SD data, including the largest tank signal and the risetimes, are entirely consistent with this range of primary energies.

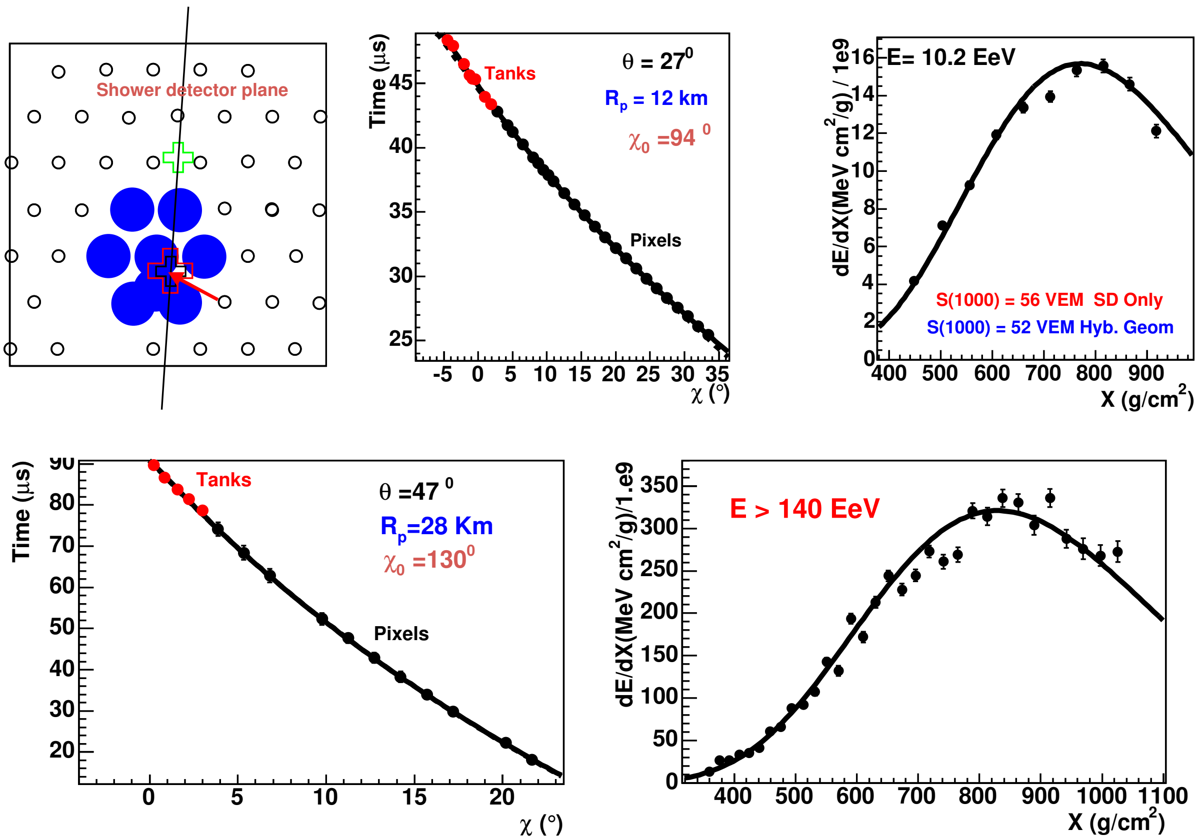

Figure 2. Top: Example of an energetic hybrid event (10.2 EeV). At left, the green cross shows the core from the FD (only) fit, overlapping black and red crosses show the results from SD and from the hybrid fit. The line indicates the shower-detector plane, the arrow the event direction. The center panel shows the hybrid time fit of χ_0-R_p-T_0, where red (black) points correspond to surface detectors (pixels in the FD camera). On the right are results of the profile fit, showing energy deposited vs. atmospheric depth. The solid line is the Gaisser-Hillas function that best fits the data. **Bottom:** The highest energy event recorded by the FD, with energy >140 EeV. It did not meet the selection criteria required for inclusion in energy spectrum[1], because the core fell outside the boundary of the SD.

References

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