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A detailed presentation of the highest-energy cosmic rays recorded at the Pierre Auger Observatory

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Abstract. A catalog that contains details of the highest-energy cosmic rays, recorded by the Pierre Auger Collaboration between 1 January 2004 and 31 December 2020, is presented. Data from 100 air showers, generated by particles having energies in the range 78 EeV to 166 EeV, are described, together with nine other very energetic events used in the energy calibration. The catalog has been created to demonstrate the quality of the data that underlie measurements reported by the Collaboration, and to make the details of these events available for scrutiny. After a brief description of the techniques used for data acquisition and reconstruction, the contents of the catalog will be described. Some events within the catalog will be discussed in detail.

1 Introduction

The Pierre Auger Observatory, located in Malargüe, in the Province of Mendoza (Argentina), is largest cosmic ray observatory in the world and is used to study the extensive air-showers produced by cosmic rays above $\sim 10^{17}$ eV [1]. The Observatory features an array of 1600 water-Cherenkov particle detector (the Surface Detector, SD) spread over 3000 km^2 on a 1500 m triangular grid, overlooked by 24 air-fluorescence telescopes (the Fluorescence Detector, FD). The Observatory is at a mean altitude of about 1400 m, corresponding to an atmospheric overburden of about 875 g/cm^2. Data-taking started on 1 January 2004 with 154 water-Cherenkov detectors and one fluorescence detector in operation. Installation was completed in June 2008 and running has been on-going since that date.
At the beginning of operation, in 2005, the Auger Collaboration presented a list of the 10 most energetic events detected until then, with the aim to illustrate the quality of the information that they contained [2]. After the conclusion of Phase I of operation, occurred on 31 December 2020, the Pierre Auger Collaboration released a catalog to demonstrate the quality of the data that lie behind measurements of the energy spectrum, the mass composition and the distribution of arrival directions of the highest-energy cosmic rays, and to make the details of these events available for scrutiny [3].

2 The Catalog

The catalog contains the 100 most energetic events recorded using the Surface Detectors of the Pierre Auger Observatory and included in the data set used in the analysis of the arrival directions of events above 32 EeV [4]. In addition nine hybrid events used in the energy-calibration procedure are presented. The energy of the particles described in the catalog is in the range 78 to 166 EeV. The catalog is described in a paper accecpeted for publication by the Astrophysical Journal Supplement Series, and in available online event browser containing details of all 109 events [5]. For each shower, the catalog contains the footprint at ground, the footprint in a plane perpendicular to the arrival direction, the lateral distribution function (LDF), and the time delays in each triggered WCD with respect to a plane shower front. Moreover the calibrated waveforms from Flash Analog-to-Digital converters (FADCs) associated with each of the three photomultipliers in the water-Cherenkov detectors (WCDs) are provided. Some peculiar FADC traces are described in detail. The events are identified with a catalog number (#*N*), and by an identifier, PAOddmmyy, that indicates the day, month and year of detection. A typical event of the catalog is shown in Figure 1.

2.1 Vertical events

The reconstruction of the arrival direction and of the size of an extensive air-shower is obtained from the magnitudes and temporal distributions of signals detected in each SD station. Different methods are used to reconstruct events with a zenith angle $\theta < 60°$, vertical events, and with $\theta > 60°$, inclined events. As the zenith angle increases, the shower loses its circular symmetry, due to the effect of the geomagnetic field, and to geometrical and attenuation effects acting as the particles cross the atmosphere. The methods used to reconstruct the inclined events are

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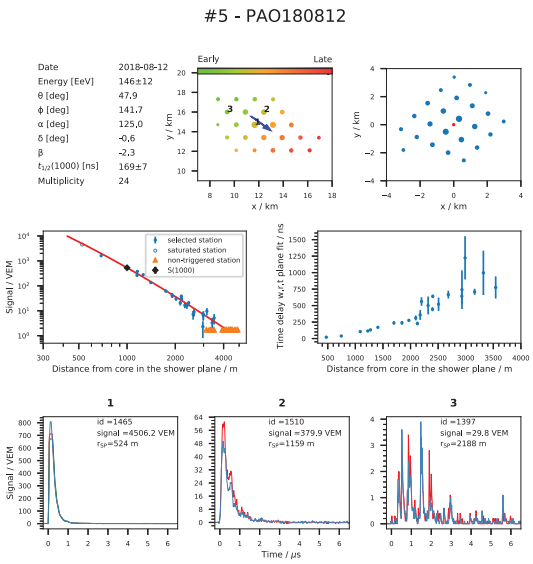

Figure 1. An event of the catalog, PAO180812 (#5). Top panel: the reconstructed features of the shower (left); the footprint at ground (middle) and in a plane perpendicular to the shower arrival direction (right). Middle panel: the lateral distribution function (left) and the time delays with respect to a plane shower front (right). Bottom panel: FADC traces of three water-Cherenkov detectors (different lines correspond to the three calibrated photomultipliers).

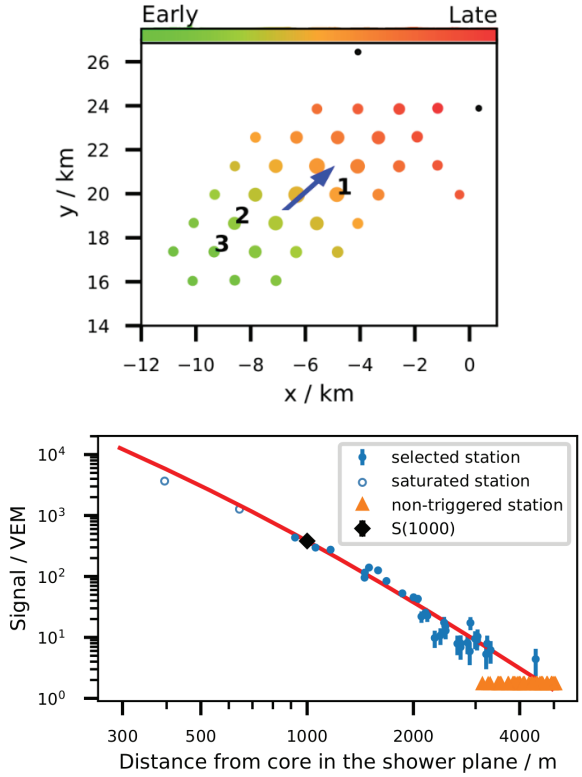

Figure 2. *Top*: Footprint on the ground of the most energetic shower detected at the Pierre Auger Observatory, PAO191110 (#1), with 34 WCDs triggered. Black dots correspond to stations that were triggered randomly. *Bottom*: The lateral distribution function of the same event. Open circles indicate saturated stations.

described in detail in [6]. The estimator of the shower size is found by fitting the observed signals to a lateral distribution function. A modified NKG function [7], [8], [9] is adopted for the procedure:

$$S_{\mathrm{LDF}}(r) = S(1000)\left[\left(\frac{r}{r_{\mathrm{opt}}}\right)\left(\frac{r+r_{\mathrm{s}}}{r_{\mathrm{opt}}+r_{\mathrm{s}}}\right)\right]^{\beta}$$

with r_{s} fixed at 700 m. The slope factor, β, changes from about -2.6 at $\theta = 0°$ to about -1.9 at $60°$. The value r_{opt} depends on the spacing of the array, and is the distance at which the uncertainty in the signal size due to shower-to-shower fluctuations is minimized. For a 1500 m spaced array, as the Pierre Auger Observatory, r_{opt} is close to 1000 m. The size of the shower at 1 km from the core, $S(1000)$, is the energy estimator.

The LDF of the most energetic event ever detected at the Pierre Auger Observatory is shown in Figure 2 together with the shower footprint at ground. This shower, PAO191110 (#1), triggered 34 stations over an area of $\sim (13 \times 6)\,\mathrm{km}^2$. The energy of the shower is 166 EeV, the zenith angle is 58.6° . This event has two saturated stations. These events are extremely rare, only three events in the full data sample have two detectors that are saturated simultaneously.

2.2 Inclined Events

Events with zenith angles > 60° are important to enhance the exposure of the Observatory by 30%, and to extend sky coverage to regions that would otherwise be inaccessible. The procedures developed to analyze these events differ from those used to reconstruct vertical showers, and are discussed in detail in [10]. Above 70° most of the particles at detector level are energetic muons accompanied by an electromagnetic component which makes up 25% of the signal beyond ~1 km from the core and around 30% within 1 km. The number of triggered stations above 60° increases with $\sec\theta$. For a shower with energy 30 EeV the average number is ~25 at 60°, while at 80° it is ~45. The method used for reconstruction is based on fitting the signal pattern recorded to what is predicted from modeling the shower development. The muon density scales with energy as $\rho_\mu(r) \propto E^\alpha$ with α in the range 0.90 to 0.95. The expected density of muons at the ground is given by

$$\rho_\mu(r) = N_{19}\,\rho_{\mu,19}(r,\theta,\phi),$$

where N_{19} is chosen by convention as a measure of the shower size using a reference shower model and comparing the signals to those expected from simulated showers of 10 EeV with the same arrival direction. Simulations have shown that $\rho_{\mu,19}(r,\theta,\phi)$, at fixed zenith and azimuth angle, varies by only about 5% for changes in the energy (between 10^{18} and 10^{20} eV) and mass of the primary particle [11].

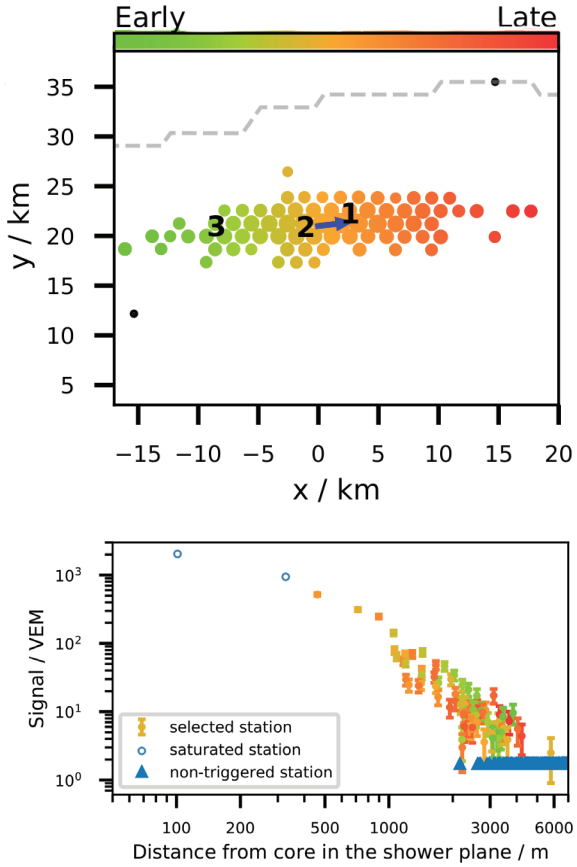

Figure 3. *Top*: Footprint on the ground of the most-energetic inclined shower detected at the Pierre Auger Observatory, PAO150926 (#17). *Bottom*: The distribution of the recorded signals as a function of the distance of the same event.

Some features of the most-energetic inclined event, PAO150926 (#17), are shown in Figure 3. The reconstructed energy of the shower is (113 ± 14) EeV and the zenith angle is $\theta = 77.2°$. The shower triggered 75 WCDs in an elongated pattern on the ground, over an area close to $(35 \times 6)\,\mathrm{km}^2$. Since the distribution of the integrated signal on the ground loses the near-rotational symmetry characteristic of vertical events, it cannot be described by a single rotationally-symmetric function.

2.3 Hybrid Events

An event that is acquired simultaneosly by an FD telescope and at least by one SD station is called hybrid. Measurements of the fluorescence and Cherenkov emission, through the FD, give details of the longitudinal development of air showers in the atmosphere, with the determination of the depth at which the deposition of energy is greatest, the shower maximum, $X_{\max}$. This is a key measurement for mass estimation (see [12] and [13]). A subsample of hybrid events can be fully reconstructed by both the FD hybrid reconstruction and, independently, by the SD reconstruction. These events are used for the calibration of the SD energy estimator with the calorimetric measurement performed by the FD. The catalog contains the ten most energetic events of the calibration subsample.

The camera of each telescope contains 440 photomultipliers (pixels). The energy deposited in the slant-depth is estimated from the light flux collected by each pixel in 100 ns interval. The resulting profile is fitted using the universal shower profile function described in [14],

$$f(X) = \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\max} \left(1 + \frac{R}{L}(X - X_{\max})\right)^{1/R^2} \exp\left(-\frac{X - X_{\max}}{RL}\right),$$

where $f(X)$ is the energy deposit at the slant-depth X and $(\mathrm{d}E/\mathrm{d}X)_{\max}$ is the energy deposit at shower maximum. R and L are shape parameters loosely constrained in the fit to the average of measured values [15]. The universal shower profile function is a modified version of the Gaisser-Hillas functional form [16].
The energy of each event is determined by integrating the area defined by the longitudinal profile, $f(X)$, with the addition of the energy that is carried into the ground largely by muons and neutrinos and that is not deposited in the atmosphere [17]. This invisible energy amounts to 20% of the at 0.1 EeV and 12% at 100 EeV. Above 10 EeV, the energy is determined with a systematic uncertainty of ~14% [15]. The methods by which data from the surface detectors are calibrated to obtain the energies of the primaries are described in [18]. Hybrid events are used for the calibration of both vertical showers and inclined events.
The energy resolution, at the highest energies, is ~8% for vertical events [19] and 12% for inclined ones.

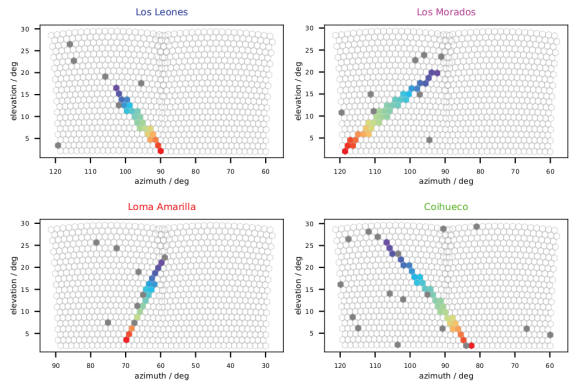

Figure 4. The camera views at the four sites where the event PAO100815, #84, was detected. The colors (violet to red) represent the time (early to late) at which the light reaches each pixel. Dark grey pixels indicate pixels that were triggered randomly.

In the most energetic hybrid event, PAO100815 (#84), the fluorescence light was detected at all four FD stations. The camera views of all telescopes at the four sites where the event was detected are shown in Figure 4. The reconstructed profiles of the energy deposition in the atmosphere are shown in Figure 5-Bottom. The lateral distribu-

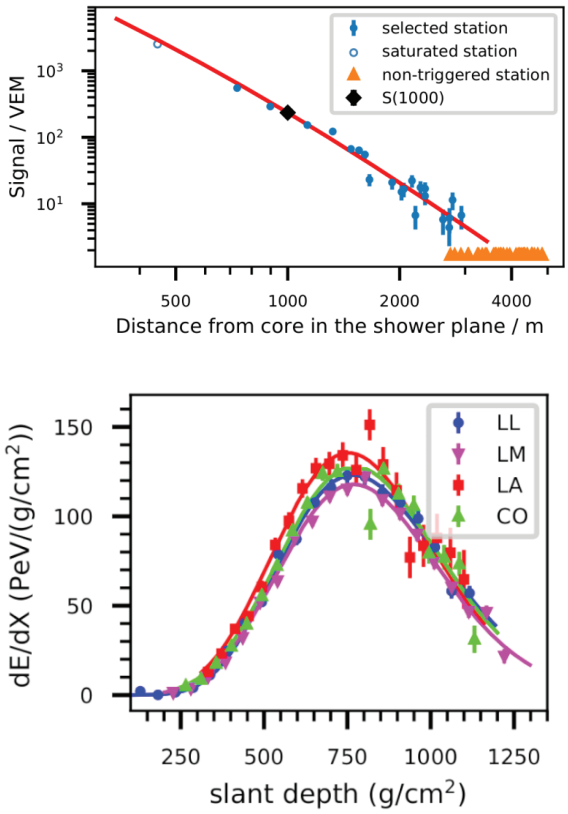

Figure 5. *Top*: The lateral distribution function of the most energetic hybrid event detected at the Pierre Auger Observatory, PAO100815, #84. *Bottom*: Profiles of the energy deposits reconstructed in each FD site. The solid lines correspond to fits to the profiles of the energy deposition using the universal shower profile function.

tion of signals is shown in Figure 5-Top. The energy estimate from the determination of $S(1000)$ is (82 ± 7) EeV. It is consistent with that from the fluorescence measurements of (85 ± 4) EeV.

2.4 Typical FADC traces

For each event, the catalog includes the FADC traces of the three photomultipliers of all triggered stations. The FADCs have 10-bit dynamic range and 40 MHz sampling rate. From the FADC information, the amplitude and time structure of each signal are obtained. Some typical signals are shown in Figure 6.

A typical signal produced a 1 km from the core in a vertical event is shown in Figure 6-a. The early parts of the signals are produced mainly by muons, while the tails are populated with broader signals due to the electromagnetic component of the shower. In an inclined event, electromagnetic particles are mostly absorbed in the atmosphere and the signals at the ground are produced almost entirely by muons, that reach a station in about 200 ns producing narrow FACD traces (Figure 6-b).
When the core of a shower falls close to a detector, within about 500 m, the large amount of particles generates a signal that can saturate the dynamic range of the electronics. An example is shown in Figure 6-c. A peculiar signal, with a spike at about 6 µs, is shown in Figure 6-d. Such signals are due to a contribution from direct light reaching one photomultiplier and are likely caused by the passage of a particle close to the location of the photomultiplier.

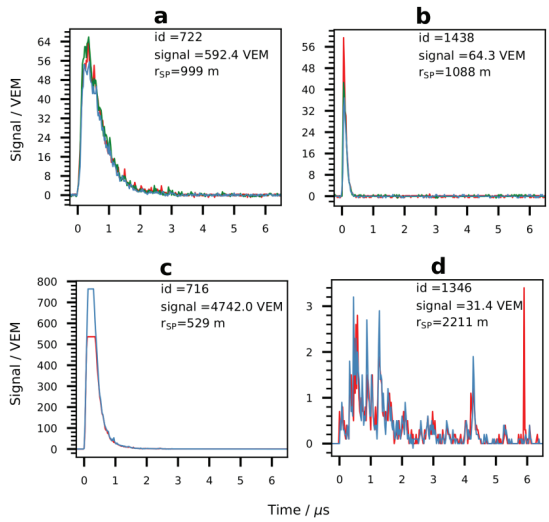

Figure 6. Some typical calibrated FADC traces of the WCDs. The different colors indicate the signals from the photomultipliers in each detector. In detectors #716 and #1346 two of the three photomultipliers were operational.

3 Conclusions

After the conclusion of Phase I of operation, the Pierre Auger Collaboration released a catalog containing the most energetic events recorded using the detectors of the Observatory. The catalog is described in a paper, and an event browser containing details of all events is available online.

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