Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research A 588 (2008) 207–210
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

The analysis of hybrid events in the Pierre Auger Observatory

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Available online 17 January 2008

Abstract

The Pierre Auger Observatory detects ultra-high energy cosmic rays by implementing two complementary air-shower measurements. The combination of the single tank information from the surface detector (SD) and the calorimetric measurements of the shower profile using the fluorescence detector (FD), known as the "hybrid" technique, provides a more reliable event reconstruction than using either detector alone. In this paper the approach used to evaluate the cosmic ray flux using this class of events is described. The analysis method is discussed considering its main steps: the event selection, the detector up time evaluation and the exposure calculation.

PACS: 95.55.Vj; 95.85.Ry; 98.70.Sa

Keywords: Pierre Auger Observatory; UHECR spectrum; Hybrids; Fluorescence

1. Status of the Pierre Auger Observatory

The Pierre Auger Observatory is the largest extensive air-shower experiment in the world. In its final configuration it will consist of two sites, one in each terrestrial hemisphere. This will allow to reach a full sky coverage, crucial for anisotropy studies [1]. Each site will be instrumented with an array of surface detectors (SDs) overlooked by a group of fluorescence telescopes. The southern site of the Pierre Auger Observatory is located in Malargüe, province of Mendoza, Argentina. An area of about 3000 km^2 is going to be instrumented with 1600 Cherenkov tanks with a 1.5 km spacing. By August 2007 about 1500 detector stations have been deployed. The location and the status of the southern site are shown in Fig. 1. The tanks forming the Auger SD is overlooked by four fluorescence sites: Los Leones, Los Morados, Loma Amarilla and Coihueco. The construction of the fluorescence detectors (FD) is already completed and all the four FD are currently taking data.

Each site is constituted of six independent optical units (telescopes). Each unit houses a Schmidt optical system composed of a segmented mirror and a 20×22 PMT pixel camera, each pixel viewing $1.5^\circ \times 1.5^\circ$. The signal from the camera is read by a FADC electronics providing a time resolution of 100 ns.

Employing two different detection techniques, the observatory allows the reconstruction of EAS with two complementary measurements. The SD array samples particle densities as the air shower arrives at the Earth's surface. The SD has almost 100% duty cycle [2]. The FD provides a calorimetric, model-independent energy measurement, because the fluorescence light production is proportional to energy dissipation by a shower in the atmosphere. This method can be used only during moonless and clean nights, and thus has roughly a 10% duty cycle [3]. A sub-sample of air showers detected and reconstructed independently by both instruments ("Golden" events) can be used to calibrate the energy scale of the SD array [4]. A complementary way to use the hybrid events is to select a sample of FD events that have at least one trigger tank. The use of these events, the so-called "Brass Hybrids", is the main topic of this work. They allow

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0168-9002/$ - see front matter
doi:10.1016/j.nima.2008.01.041

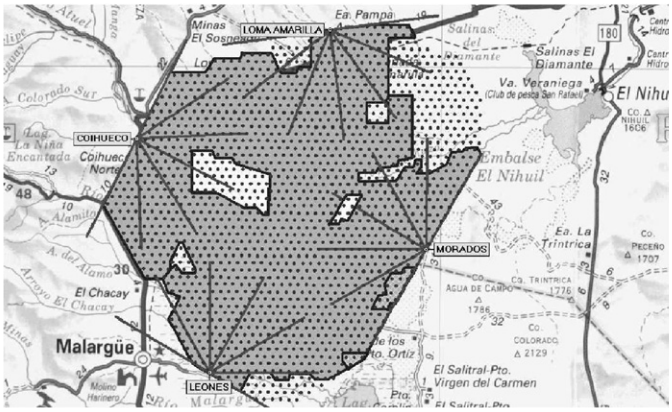

Fig. 1. The southern site of the Pierre Auger Observatory. Dots represent the position of the 1600 tanks that will cover a 3600 km^2 area. The dark grey area shows the amount of tanks deployed by August 2007. The surface detector is overlooked by four fluorescence telescopes: Los Leones, Los Morados, Loma Amarilla and Coihueco.

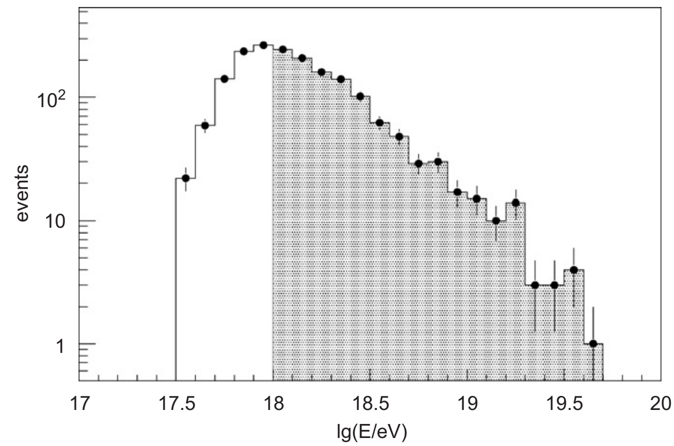

Fig. 2. Energy distribution of the selected data. The number of events that survive the cuts, in the selected period, is 1814. Only 1092 events with energy $E > 10^{18}$ eV are used for this analysis (shadowed area).

both to increase statistics with respect to the "Golden" events and improve the reconstruction with respect to "FD mono" ones [3].

2. Data selection

For this analysis the data collected from December 2004 up to February 2007 are used. However, most of these events, do not allow a precise determination of shower parameters. In order to increase the energy resolution of events a set of quality criteria was applied. Only events with a successful hybrid geometry reconstruction and a reconstructed zenith angle lower than 60° are accepted for this analysis. To suppress monocular events with random SD triggers, we required the station used for the reconstruction to lie within 750 m from the shower axis. This condition ensures the full efficiency for the single tank trigger. Events that are expected to develop outside the geometrical field of view of the FD are also rejected and, based on data, a fiducial volume for shower detection is defined (see details in Refs. [10,11]) as a function of the reconstructed energy. The observed shower profile and reconstructed depth at maximum ($X_{\max}$) are required to satisfy the following conditions:

- a successful Gaisser–Hillas fit with $\chi^2/\mathrm{Ndof} < 2.5$ for the reconstructed longitudinal profile;
- $X_{\max}$ between minimum observed depth and maximum observed depth;
- relative amount of Cherenkov light in the recorded signal lower than 50%;
- measurement of atmospheric parameters available.

Finally, as the algorithm used for the reconstruction of the shower profile[1] propagates both, light flux and geometrical uncertainties, the estimated uncertainties of shower energy are a powerful estimator of the reconstruction quality. Only events with $\sigma(E)/E < 20\%$ are selected. In Fig. 2 the energy distribution of events, once all quality cuts have been applied, is shown.

3. Hybrid exposure

The calculation of the hybrid exposure relies on a detailed simulation of FD and SD response.

For a given detector configuration the exposure, as a function of primary shower energy, is

$$\mathcal{E}(E) = \int_{\Omega}\int_{A_{\mathrm{gen}}} \varepsilon(E)\,\mathrm{d}S\cos\theta\,\mathrm{d}\Omega \cdot \Delta T \qquad (1)$$

where ΔT is the considered time interval, $\varepsilon(E)$ is the detection efficiency including quality cuts, dS are, respectively, the differential and total generation areas, $\mathrm{d}\Omega = \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi$ and Ω are, respectively, the differential and total solid angles. ϕ goes from 0 to 2π and θ from 0 to a maximum angle. Several factors (fast growth of surface array and ongoing extension of the FD, seasonal and instrumental effects) obviously introduce changes of the detector configuration with time. In this case the hybrid exposure is obtained summing up the contributions coming from the different configurations.

In order to reproduce the exact working conditions of the experiment and the entire sequence of given configurations, a large sample of Monte Carlo data have been produced. The effect of the different data taking configurations has been taken into account and simulated using an accurate calculation of the hybrid detector uptime.

The simulated data sample consists of longitudinal energy deposit profiles generated using CONEX [6] code. The energy spectrum ranges from 10^{17} to 10^{21} eV according to a power-law function with differential spectral index -2 (reweighted to -2.8 when comparing data to simulation) and the zenith angles are sampled between 0° and 70°. The

[1] For the energy reconstruction a fluorescence photon yield according to Ref. [12] was used.

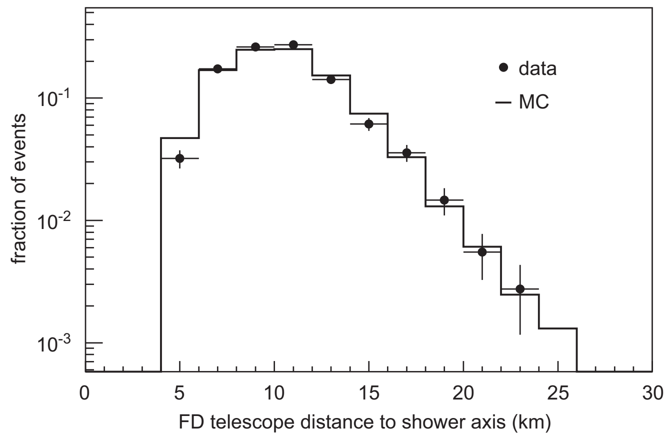

Fig. 3. Comparison between data and Monte Carlo. Distribution of FD telescope distance to shower axis.

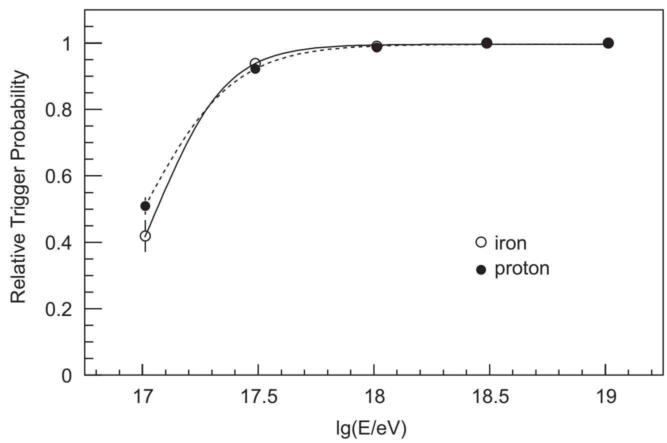

Fig. 4. Hybrid trigger efficiency for proton and iron primaries from the full CORSIKA simulation method.

simulation has been validated by comparing the distribution of reconstructed observables to experimental ones. In Fig. 3 the distributions of the telescope distance to shower axis, both for data and simulation, are shown. A very good agreement is found at this selection level.

The distribution of particles at ground is not provided by CONEX. However, the time of the station with the highest signal is sufficient information for this analysis. This time is needed in the hybrid reconstruction for determining the incoming direction of the showers, and the impact point at ground. Once the shower geometry is known, the longitudinal profile can be reconstructed and the energy calculated. The tank trigger simulation is performed using a parameterization based on ''Lateral Trigger Probability'' (LTPs) functions [7]. They give the probability for a shower to trigger a tank as a function of primary cosmic ray energy, mass, direction and tank distance to shower axis.

A cross check with a full hybrid simulation was performed using CORSIKA showers [8], in which FD and SD response are simultaneously and fully simulated. As it is shown in Fig. 4 the hybrid trigger efficiency (an FD event in coincidence with at least one tank) is flat

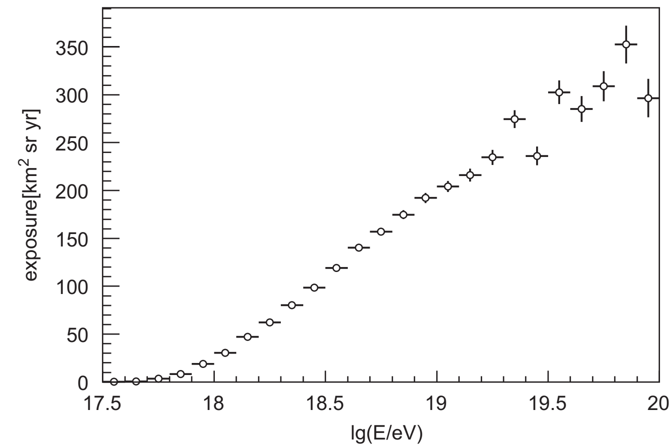

Fig. 5. Hybrid exposure as a function of shower primary energy. It refer to the last reconstruction level once all cuts have been applied.

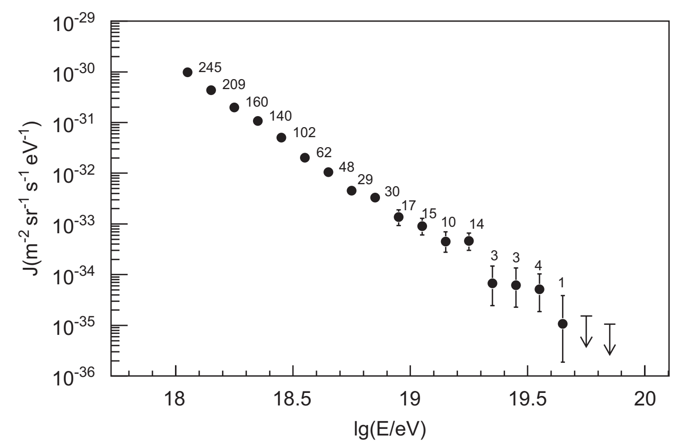

Fig. 6. Hybrid energy spectrum. Only statistical error is shown in the figure.

and equal to 1 at energies greater than 10^{18} eV. In this energy range, the hybrid trigger efficiency also coincides with the one derived on the basis of the LTPs method. Moreover the difference between the two primaries becomes negligible for energies larger than $10^{17.5}$ eV. A detailed description of the hybrid detector simulation program is given in Ref. [9]. In Fig. 5 the hybrid exposure at the last reconstruction level is shown. Exposure at this level depends very weakly on chemical composition, giving a spectrum basically independent of any assumption on primaries mass.

4. Analysis results

Using both the data selection and the hybrid exposure, the hybrid spectrum can be derived. In Fig. 6 the hybrid spectrum is shown as a function of primary energy, only statistical error is given.

Moreover the hybrid spectrum is affected by the systematic uncertainties. Individual contributions are shown in Fig. 7 as a function of energy. The uncertainty

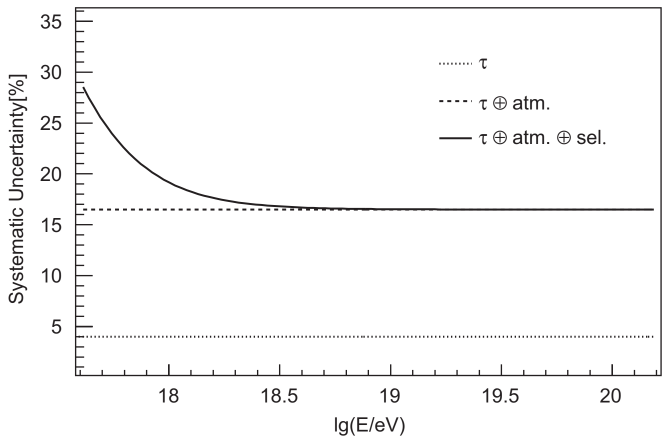

Fig. 7. Systematic uncertainties on hybrid spectrum due to uptime (τ), atmospheric conditions (atm) and propagation of the energy scale uncertainty on the event selection (sel). All the errors are summed up in quadrature.

on the energy determination is quoted to about 22% [3]. The detector uptime has been independently cross-checked using the observed laser shots fired by the Central Laser Facility (CLF) [13]. The agreement of the two analysis is at the level of 4%. A more significant source of uncertainty (16%) comes from the lack of a precise knowledge of atmospheric conditions. In fact, part of the shower profile may be shadowed by clouds or the Cherenkov light can be diffused by fog and/or clouds and redirected towards the detector. However, this uncertainty is expected to be reduced with the improvement of atmospheric monitoring data analysis. Finally, an energy dependent uncertainty is expected as a consequence of the aperture calculation at reconstruction level. It is due to the efficiency of the event selection algorithm that varies with energy and is very sensitive to a systematic energy shift. All contributions are summed up in quadrature giving an overall uncertainty of about 20% at $E = 10^{18}$ eV (see Fig. 7).

5. Conclusions

A class of events (Brass Hybrids) has been characterized as a suitable sample for physics analysis. More than two years of hybrid data have been used to measure the energy spectrum of cosmic rays above 10^{18} eV. In spite of their low statistics the use of Brass Hybrids allow to extend the Auger spectrum below $10^{18.5}$ eV. These events allow a robust determination of shower maximum and consequently a more reliable study of mass composition (see Ref. [15]). Moreover a good agreement with the spectrum measured by the SD has been found (see Refs. [4,5]) within the estimated FD systematic uncertainties. Details about the shape of the hybrid spectrum and its astrophysical interpretation are out of the aim of this paper and can be found in Ref. [14].

References

[1] The Pierre Auger Collaboration, Astropart. Phys. 27 (2007) 244.
[2] T. Suomijärvi, for the Pierre Auger Collaboration, in: Proceedings of the 30th ICRC, Merida, 2007, p. 299.
[3] B. Dawson, for the Pierre Auger Collaboration, in: Proceedings of the 30th ICRC, Merida, 2007, p. 976.
[4] M. Roth, for the Pierre Auger Collaboration, in: Proceedings of the 30th ICRC, Merida, 2007, p. 313.
[5] L. Perrone, for the Pierre Auger Collaboration, in: Proceedings of the 30th ICRC, Merida, 2007, p. 316.
[6] T. Bergmann, et al., Astropart. Phys. 26 (2007) 420.
[7] E. Parizot, for the Pierre Auger Collaboration, in: Proceedings of the 29th ICRC, vol. 7, Pune, 2005, pp. 71–74.
[8] D. Heck, et al., Report FZKA 6019, 1998.
[9] L. Prado, et al., Nucl. Instr. and Meth. 545 (2005) 632.
[10] M. Unger, for the Pierre Auger Collaboration, in: Proceedings of the 30th ICRC, Merida, 2007, p. 594.
[11] The Pierre Auger Collaboration, Astropart. Phys. 27 (2007) 155.
[12] M. Nagano, et al., Astropart. Phys. 22 (2004) 235.
[13] S. BenZvi, for the Pierre Auger Collaboration, in: Proceedings of the 30th ICRC, Merida, 2007, p. 399.
[14] T. Yamamoto, for the Pierre Auger Collaboration, in: Proceedings of the 30th ICRC, Merida, 2007, p. 318.
[15] A.A. Watson, for the Pierre Auger Collaboration, this conference.