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Exposure of the Hybrid Detector of The Pierre Auger Observatory

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Abstract: The exposure of the Pierre Auger Observatory for events observed by the fluorescence detector in coincidence with at least one station of the surface detector is calculated. All relevant monitoring data collected during the operation, like the status of the detector, background light and atmospheric conditions are considered in both simulation and reconstruction. This allows to realistically reproduce time dependent data taking conditions and efficiencies.

Introduction

The measurement of the cosmic ray flux above 10^{18}eV is one of the foremost goal of the Pierre Auger Observatory[1]. In this energy region the transition between the galactic and the extragalactic component of cosmic rays is expected to occur[2]. The signature of this transition is widely believed to be associated with a flattening of cosmic rays energy spectrum, identified as the *ankle*. An accurate determination of the ankle could help to discriminate among theoretical models[3, 4, 5].

The hybrid approach is based on the detection of showers observed with the Fluorescence Detector (FD) in coincidence with at least one station of the Surface Detector (SD). Although a signal in a single station doesn't ensure an independent trigger in SD [6], it is a sufficient condition for a very accurate determination of the shower geometry.

The measurement of cosmic ray flux relies very much on the precise determination of detector exposure that is influenced by several factors. The response of the hybrid detector is in fact very much dependent on energy, distance of recorded event, atmospheric and data taking conditions.

Hybrid Exposure

The flux of cosmic rays J as a function of energy is defined as:

$$J(E) = \frac{1}{\Delta E}\frac{N^D(E)}{\mathcal{A}(E)T}; \qquad (1)$$

where $N^D(E)$ is the number of detected events in the energy bin E, $\mathcal{A}(E)$ is the energy dependent aperture of the detector, T is the on-time of the detector and ΔE is the width of the energy bin E. The product $\mathcal{A}(E)T$ is usually referred to as the exposure, $\mathcal{E}(E)$.

The exposure, as a function of primary shower energy, can be written as:

$$\mathcal{E}(E) = \int_T \int_\Omega \int_{A_{gen}} \varepsilon(E)\ \mathrm{d}S\ \ \cos\theta\ \mathrm{d}\ \Omega\ \mathrm{d}T; \qquad (2)$$

where $\varepsilon(E)$ is the detection efficiency including quality cuts, dS and A_{gen} 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. Several factors (fast growth of surface array and ongoing extension of the fluorescence detector, 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 (i.e times).

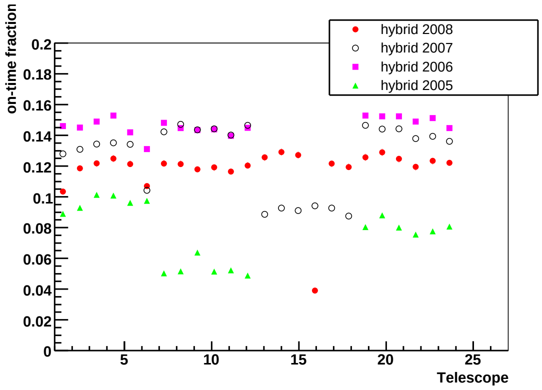

Figure 1: The evolution of the average hybrid duty-cycle during the construction phase of the Pierre Auger Observatory.

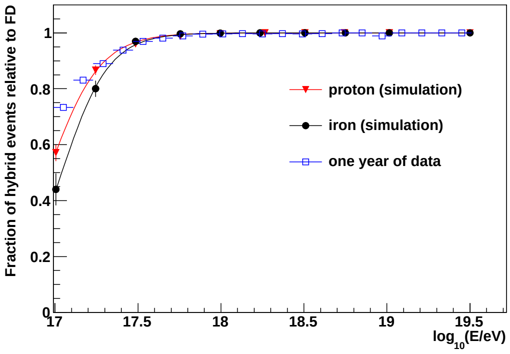

Figure 2: Relative hybrid trigger efficiency from hybrid simulation for proton and iron and data. All the events are taken for zenith less than 60°.

Hybrid On-Time

If we want to calculate the hybrid exposure we need to know the detector on-time. The efficiency of fluorescence and hybrid data taking is influenced by many effects. These can be external, e.g. lightning storm, or internal to the data taking itself, e.g. DAQ failures. In order to be able to determine the on-time of our hybrid detector it is therefore crucial to take as many of these possibilities into account and derive a solid description of the(time dependent) data taking quality.

Errors can occur on different levels starting from the smallest unit of the FD, i.e. one single pixel readout channel, up to the highest level, i.e. the combined SD-FD data taking of the Observatory. In order to be able to onduct the time dependent MC simulations we have to take all known disturbances into account. To derive the on-time of the hybrid detection mode we rely on a variety of monitoring information and the data itself. As compromise between accuracy and stability we derived the complete detector status down to the single photomultiplier for time intervals of 10 min.

The time evolution of the full hybrid duty-cycle over 4 year during the construction phase of the observatory is given in figure 1. It should be noted that the telescopes belonging to the building of Los Morados (telescopes 7-13) have become operational only in May 2005 and the ones in Loma Amarilla (telescopes 14-17) have become online in March 2007. This result has been cross-checked with other independent analyses[7, 8] giving an overall agreement within about 4%.

Monte Carlo simulation and Event Selection

In order to reproduce the exact working conditions of the experiment and the entire sequence of the different occurring configurations, a large sample of Monte Carlo data have been produced. The simulated data sample consists of longitudinal energy deposit profiles generated with QJSJet-II[10] as hadronic interaction model using CONEX [11] code. As the distribution of particles at ground is not provided by CONEX, the time of the station with the highest signal is simulated in a fast way according to the muon arrival time distribution[12]. This time is needed in the hybrid reconstruction for determining the incoming direction of the showers, and the impact point at ground.

The effect of the different data taking configurations has been taken into account and simulated using the calculation of the hybrid

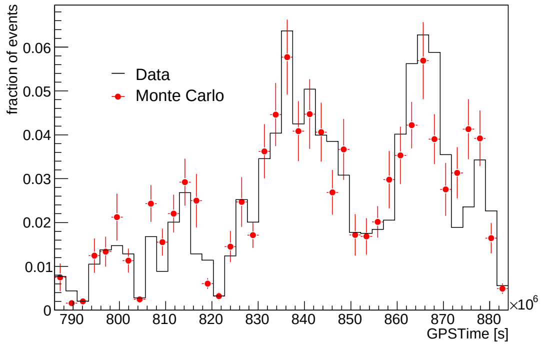

Figure 3: Data MC Comparison: fraction of hybrid events as a function of time starting from November 2005. Both data (black line) and MC (red solid circles) are shown.

detector on-time. Moreover the influence of clouds and atmospheric conditions on the exposure calculation have been taken into account using the information of the atmospheric monitoring[9] of the Pierre Auger Observatory.

A full hybrid simulation was performed using CORSIKA showers [14], in which FD and SD response are simultaneously and fully simulated. As it is shown in Figure 2 the hybrid trigger efficiency (an FD event in coincidence with at least one tank) is flat and equal to 1 at energies greater than 10^{18} eV. The difference between the two primaries becomes negligible for energies larger than $10^{17.5}$ eV. Moreover the comparison with data shows a very good agreement. This simulation has been used to parameterize the response of the SD stations using the LTPs[15] and follow both the deployment and the inefficiencies of the array. The simulations were performed within the Auger analysis framework[13].

Once the shower geometry is known, the longitudinal profile can be reconstructed and the energy calculated in the same way as the data. Finally the same quality cuts used for calculating the hybrid spectrum are applied. A first set of cuts based on the quality of the geometrical reconstruction:

- reconstructed zenith angle less than 60°;
- station used for the hybrid reconstruction lying within 1500 m from the shower axis;
- energy dependent core-FDsite distance according to [16];
- energy dependent f.o.v according to [17].

A second set of cuts based on the quality of the reconstructed profile:

- a successful Gaisser-Hillas fit with $\chi^2/\mathrm{Ndof} < 2.5$ for the reconstructed longitudinal profile
- minimum observed depth $< X_{max} <$ maximum observed depth;
- events with relative amount of Cherenkov light in the signal less than 50%;
- energy reconstruction less than 20%;
- measurement of atmospheric parameters available[18, 9];
- cloud coverage from Lidar[9] measurements lower than 20%.

Then the reliability of quality cuts has been checked by comparing the cut parameter distribution of data and MC. As an example the fraction of hybrids events as a function of time is shown in Figure 3. In this plot both the growing of the hybrid detector and the seasonal trend of the hybrid data taking efficiency are visible. The data are in a very good agreement with the MC prediction.

Results

The result of the calculation of the exposure is shown in Figure 4 both for proton an iron primaries.

The exposure has been corrected for a 4% systematic uncertainty derived from the analysis of CLF laser shots[18]. The analysis has shown ....

Thanks to the quality cuts the dependence of the exposure on the primary mass composition is reduced. At 10^{18} eV the difference of pure proton/iron exposure with respect to a mixed composition (50% proton - 50% iron) exposure is about 8% and decreases to 1% at higher energies.

In Figure 5 it is shown the growth of the hybrid exposure as a function of time for different energies. Jumps in the exposure are visible for periods of high deployment rate of SD stations.

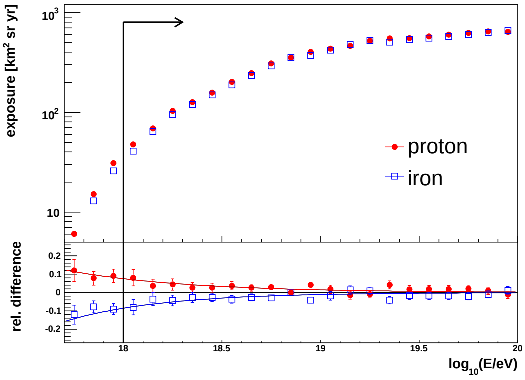

Figure 4: The hybrid exposure for proton (red solid dot) and iron (blue open squares) primaries derived from MC simulation.

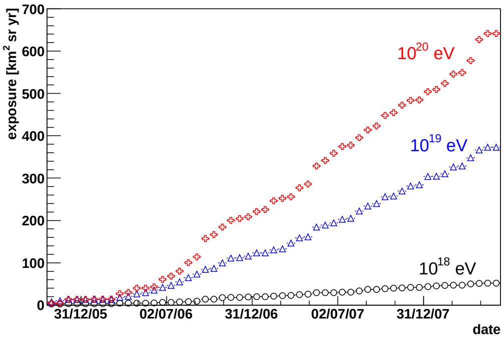

Figure 5: The growth of the hybrid exposure as a function of time starting from November 2005 up to May 2008 for different energies.

The effect is more effective at higher energies ....

P(FD—SD)?

Conclusions

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