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Measurement of the UHECR energy spectrum from hybrid data of the Pierre Auger Observatory

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Abstract: More than two years of fluorescence detector data collected in coincidence with at least one station of the surface detector array ("hybrid data") are used to measure the flux and energy spectrum of cosmic rays above about 10^{18} eV. The hybrid measurement extends towards lower energies the spectrum measured with the surface detector data only, and provides a cross-check with an independent data set. The determination of the fluorescence detector aperture and of its live-time, which is the major aspect of this measurement, is illustrated in detail. Our current estimate of the corresponding systematic uncertainties are given.

Introduction

The Pierre Auger Observatory employs two independent detection techniques, allowing the reconstruction of extensive air showers with two complementary measurements. Indeed, the combination of information from the surface array and the fluorescence telescopes enhances the reconstruction capability of "hybrid" events with respect to the individual detector components. A description of the hybrid performance of the Pierre Auger Observatory is given in [1].

In this analysis, the energy spectrum of cosmic rays is measured using hybrid data collected between December 2004 and February 2007. The inspected energy range covers a region where the transition from Galactic to extra-galactic cosmic rays is expected to occur.

Due to construction, the configuration of fluorescence telescopes and surface detector has evolved significantly and the effective detection area has correspondingly changed. The key points of the analysis are an accurate estimate of the hybrid detector exposure and an appropriate selection of well-reconstructed events. A good knowledge of systematic uncertainties is also required to support the robustness of the results.

Hybrid Exposure

The calculation of the hybrid exposure relies on a detailed simulation of fluorescence (FD) and surface detector (SD) response. To reproduce the exact working conditions of the experiment and the entire sequence of given configurations, a large sample of Monte Carlo simulations have been performed. Several factors (fast growth of surface array and ongoing extension of the fluorescence detector, seasonal and instrumental effects) can introduce a significant dependence of aperture on time. This effect has been taken into account and simulated using an accurate calculation of the hybrid detector uptime. The simulation sample consists of a large number of longitudinal energy deposit profiles generated with CONEX [2]. The energy spectrum ranges from 10^{17}eV 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°. Fig. 1 (top) shows the number of collected events as a function of lunar months (FD measurement cycles after December 2004) for data and simulation. There is a good overall agreement along the entire time scale considered for this analysis. The simulation has been validated by comparing the distribution of reconstructed observables to

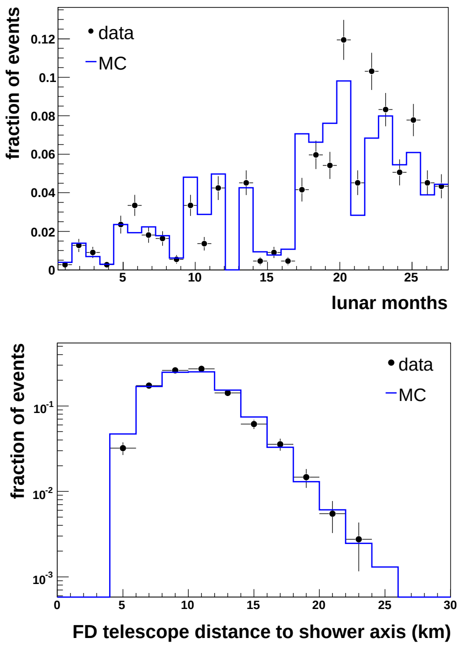

Figure 1: Fraction of events as a function of lunar months (top) and distribution of telescope distance to shower axis (bottom), for data and simulation (same selection cuts applied).

experimental data. Fig. 1 (bottom) shows the distribution of the telescope distance to shower axis, for data and simulation. A very good agreement is found at this selection level.

The distribution of particles at ground is not provided by CONEX. Nevertheless, the time of the station with the highest signal is sufficient information for this analysis. This time is used 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 parameterisation based on “Lateral Trigger Probability” functions (LTPs) [3]. 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 full hybrid simulation with CORSIKA showers [4] (FD and SD response are simultaneously and fully simulated) has shown that the hybrid trigger efficiency (a fluorescence event in coincidence with at least one tank) is flat and equal to 1 at energies greater than 10^{18} eV. This feature is shown in Fig. 2 for proton and iron primaries. For these energies, the hybrid trigger efficiency coincides with the one derived from the LTPs based method. The difference between the two primaries becomes negligible at energy larger than $10^{17.5}$ eV. A detailed description of the hybrid detector simulation program is given in [5].

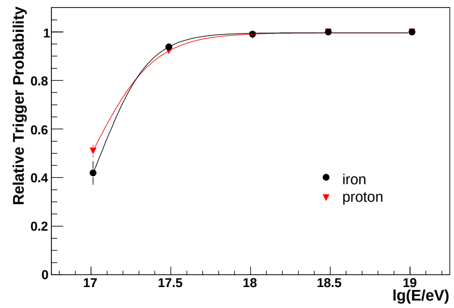

Figure 2: Hybrid trigger efficiency for proton and iron (full simulation method)

Data Selection

Only data with a successful hybrid geometry reconstruction are selected for calculating the hybrid spectrum. To suppress monocular events with random surface detector triggers, only events with the station used for reconstruction lying within 750 m from the shower axis are accepted. This condition ensures that the probability of the station to trigger is equal to one. Showers that are expected to develop outside the geometrical field of view of the fluorescence detectors are also rejected and, based on data, a fiducial volume for detection is defined as a function of the reconstructed energy. Details on how the fiducial volume is taken are given in [6] and [7]. Moreover, only events with reconstructed zenith angle less than 60° are accepted. The observed profile and reconstructed shower depth at maximum (X_{max}) are required to satisfy the following conditions:

- a successful Gaisser-Hillas fit with χ^2/Ndof < 2.5 for the reconstructed longitudinal profile

- minimum observed depth $< X_{max} <$ maximum observed depth
- a relative amount of Cherenkov light in the signal less than 50%
- measurement of atmospheric parameters available.

A fluorescence photon yield according to [8] is currently used for energy reconstruction. Finally, as the algorithm used for the profile reconstruction propagates both, light flux and geometrical uncertainties, the estimated uncertainties of shower energy is a good variable to reject poorly reconstructed showers. We require $\sigma(E)/E < 20\%$. Fig. 3 shows the hybrid exposure (top) and the energy distribution of all events (bottom) at the last reconstruction level (all quality cuts have been applied). Exposure at this level depends very weakly on chemical composition, giving a spectrum basically independent of any assumption on primaries mass. The hybrid spectrum deriving from this analysis is shown in Fig. 4 (left), compared (right) with the spectrum from surface detector presented in [9] (only statistical uncertainties are given in the figure).

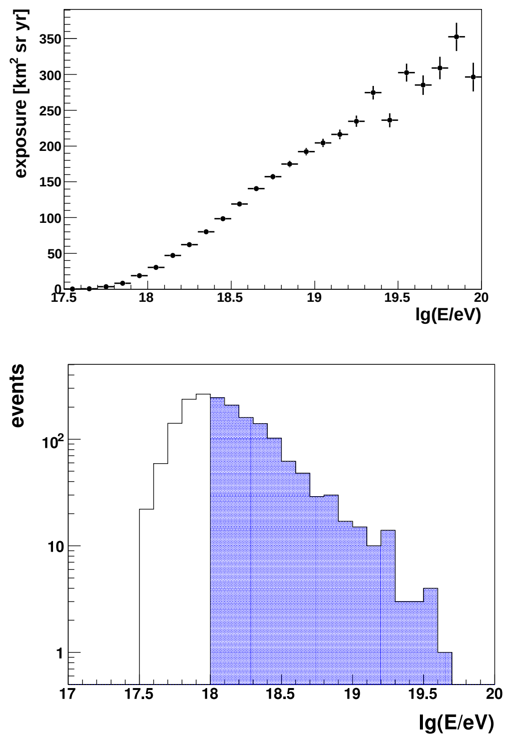

Figure 3: Hybrid exposure after all cuts (top). Energy distribution of selected data (bottom). The number of events used for the spectrum (E $> 10^{18}$ eV, shadowed area) is 1092.

Systematics

The hybrid spectrum is primarily affected by the systematic uncertainty on the energy determination (about 22% [1]). Further systematic uncertainties and their individual contributions are shown in Fig. 5 as a function of energy. The calculation of detector uptime has been independently cross-checked using the observed laser shots fired by the Central Laser Facility (CLF) [10] and the results agree at the level of 4%. A more significant source of uncertainty (16 %) is expected from the lack of a precise knowledge of atmospheric conditions. 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. This uncertainty is still large but it is expected to be significantly reduced when all atmospheric monitoring data have been fully analysed. Finally, an uncertainty, increasing at lower energies, is expected as a consequence of the aperture calculation at reconstruction level. Indeed, at low energy, the efficiency of the event selection algorithm varies rapidly with energy and is very sensitive to a systematic energy shift. An overall uncertainty (all contribution summed up in quadrature) of about 20% is expected at E=10^{18} eV (see Fig. 5). As a final remark, it is worth saying that the extension to the viewing elevations of FD telescopes will allow to be reached lower energies with smaller systematics [11].

Conclusions

More than two years of hybrid data (fluorescence events in coincidence with at least one station) have been used to measure the energy spectrum of cosmic rays above 10^{18} eV. Very good agreement with the spectrum measured by the surface detector is found within the estimated FD systematic uncertainties. A combined spectrum is presented in [12]

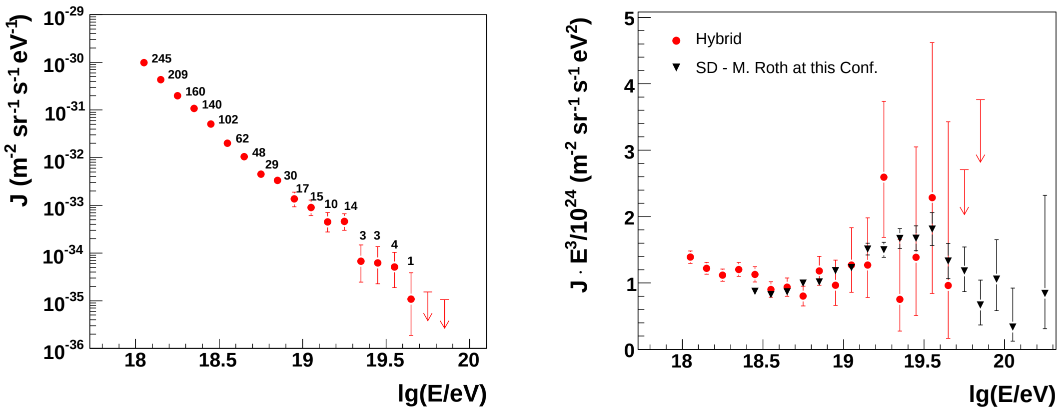

Figure 4: Hybrid energy spectrum (left) shown in comparison (right) with surface detector spectrum (only statistical uncertainties are given in the figure).

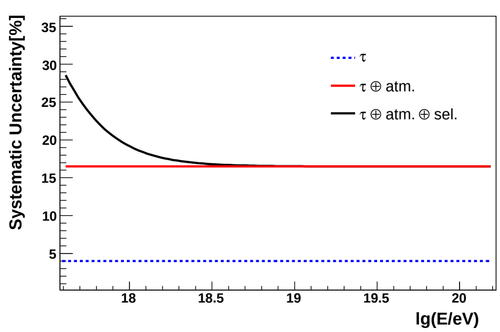

Figure 5: Systematic uncertainties on hybrid spectrum due to live time (τ), atmospheric conditions (atm) and impact of the energy scale uncertainty on events selection (sel).

and astrophysical implications are also discussed there.

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