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Validation of the Real and Simulated Data of the Pierre Auger Fluorescence Telescopes

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The fluorescence detector (FD) of the Pierre Auger Observatory is currently operating 18 fluorescence telescopes of the 24 that will be employed in the completed detector. These telescopes, grouped in 4 eyes each consisting of 6 telescopes, measure the longitudinal profile of cosmic ray showers with a 14% duty cycle. The reconstruction capability and triggering efficiency have been studied using a complete simulation and reconstruction production chain, employing both simulated CORSIKA showers and parameterised Gaisser-Hillas profiles. The propagation through the atmosphere and the detector response are taken into account and simulated in detail. These simulated data have been generated in a preliminary analysis using the method of importance sampling to efficiently cover the energy region of 0.3 - 300 EeV, various shower geometries and impact points and different primary particles. The distributions of observables have then been investigated in both real and simulated data, facilitating the validation of the reconstruction and simulation software. Comparisons of real and simulated data are discussed and used to assess their impact on the data analysis.

1. The CORSIKA simulation sample

This paper discusses the performance of the Auger fluorescence telescope, which has been studied with a large sample of fully simulated CORSIKA showers [1]. A detailed description of the Fluorescence Detector simulation program is given in [2]; the reconstruction was performed using the Auger Offline software [3]. To obtain a sufficiently large number of events the CORSIKA showers have been taken from the shower database generated in the Lyon computing centre for simulation studies with the Auger detector. The shower sample consists of 3850 proton showers and 4150 iron showers with zenith angles of 0°, 18°, 26°, 37°, 45°, 60° and energies ranging between $10^{17.5}$ and $10^{20.5}$ eV in steps of 0.25 or 0.5 in the logarithmic scale. The CORSIKA showers have been simulated in a slice of 2° in the field of view of Bay4 (Los Leones Eye), with uniformly distributed core distances. This choice has been made in order to optimise the reconstruction and trigger efficiency study as a function of core distance, rather than simulating the true distribution of cosmic ray landing points (uniformly distributed on surface). In order to minimise the inefficiency due to low energy showers landing far away from the eye (with a negligible probability of being triggered), the maximum distance of the generated impact points was to chosen to depend on the shower energy and ranges from 5 km up to a maximum of 60 km. The sensitivity of reconstructed energy to the atmospheric properties has been investigated by assuming two extreme atmospheres with aerosol horizontal attenuation lengths at sea level of 12.5 km and 24 km and scale height of 2 km.

2. Trigger efficiency and energy resolution with a given shower geometry

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 these so called "hybrid" events with respect to the individual detector components. A description of the hybrid performance of the Pierre Auger Observatory is given in [4].

In this study, the energy resolution of the fluorescence detector has been estimated for the case of known fixed shower geometry. This assumption is justified by the argument that hybrid reconstruction benefits from a more accurate shower geometry with respect to the monocular fluorescence reconstruction. Setting the geometry to the true value then provides a realistic estimate of the energy resolution for the hybrid mode. Assumptions for the atmosphere, detector calibration and fluorescence yield calculation have been made consistently throughout the simulation-reconstruction chain. Fig. 1 shows the trigger efficiency as a function of energy for increasing core distance ranges (all zenith angles merged). The trigger efficiency is 100% up to a distance of 25 km for showers with energy of 10^{19} eV. A detailed calculation of the fluorescence detector aperture for different detector configurations and using analytical shower profiles (Gaisser-Hillas functions) is given in [6]. The method adopted here for the reconstruction of shower longitudinal profiles and energies with the Auger Fluorescence telescope is described in [5]. In order to focus on "reconstructible" events only, the observed profile and reconstructed shower depth at maximum (X_{max}) are required to satisfy the following conditions:

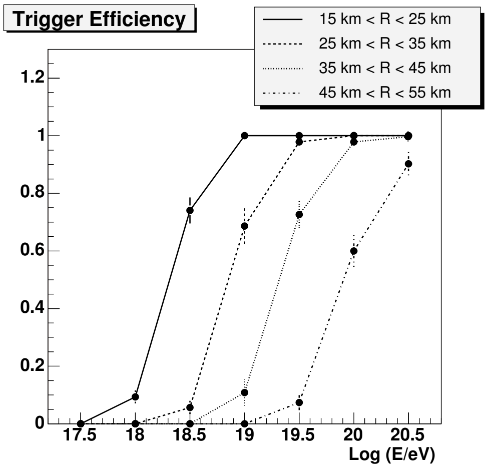

Figure 1. Trigger efficiency as a function of energy for increasing core distances ranges (all zenith angles merged).

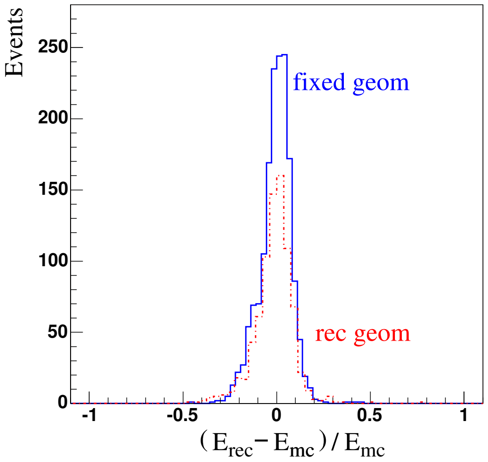

Figure 2. Energy resolution for the simulated data sample with true geometry (blue line, 1607 events, RMS=9%) and reconstructed monocular geometry (red dot-dashed line, 798 events, RMS=11%).

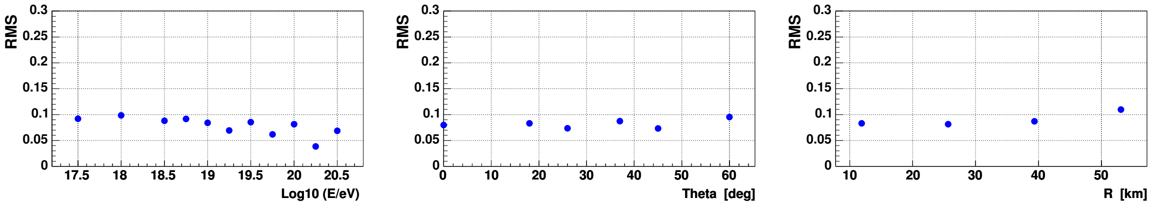

Figure 3. RMS of the residual distribution as a function of true energy (left), zenith angle (middle) and core distance (right) for fixed geometry.

- a successful Gaisser-Hillas fit with χ^2/Ndof < 5 for the reconstructed longitudinal profile
- minimum observed depth $< X_{max} <$ maximum observed depth
- a reconstructed longitudinal profile wider than 200 g cm^{-2}.

Fig. 2 shows the residual distribution of the reconstructed energy, (reconstructed energy-true energy)/(true energy), for events with fixed geometry (blue line) and with reconstructed geometry (red dot-dashed line). The energy resolution improves from 11% to 9% in terms of RMS and the number of selected events increases - by a factor 2 - if the geometry is set to the true value. This demonstrates how much the performance of the Auger Observatory can improve when operating in hybrid mode. The RMS of the residual for the case of fixed geometry is shown in Fig. 3 as a function of true energy (left), zenith angle (middle) and core distance (right). It depends weakly on the energy (improving slightly with increasing energy) and has a stable average value of about 9% over the studied core distance and zenith angle range. The energy resolution shown has been calculated for proton primaries and for a clean atmosphere (aerosol horizontal attenuation length at sea level of 24 km and scale height of 2 km). A test performed with a different atmosphere (aerosol horizontal attenuation length at sea level of 12.5 km and scale height of 2 km) shows that the energy resolution may degrade from 11% to 13% for the proton case.

Finally, the residual of the reconstructed depth at shower maximum (reconstructed X_{max} - true X_{max}) is shown for fixed geometry in Fig. 4 for proton (black line, RMS=25 g cm^{-2}) and iron (red dot-dashed line, RMS=22 g cm^{-2}).

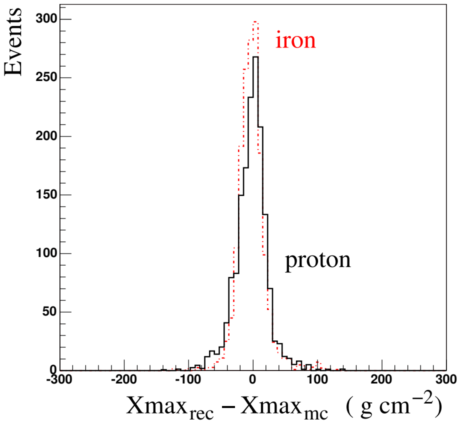

Figure 4. Residual distribution of the reconstructed depth at shower maximum (reconstructed X_{max} - true X_{max}) - fixed geometry -, for proton (black line) and iron (red dot-dashed line).

3. Comparison with experimental data

The trigger simulation has been validated by comparing the predicted number of triggered events to the experimental data. The Monte Carlo sample has the following characteristics:

- 250000 events (50% iron, 50 % proton primaries), analytical shower profiles (Gaisser-Hillas functions)
- energy spectrum generated from $10^{17.5}$eV up to $10^{20.5}$eV according to a power-law spectrum with differential spectral index -2
- zenith angles generated according to $dN/d\cos\theta \propto \cos\theta$ between 0° and 60°
- events simulated in the field of view of Bay 4 of the Los Leones eye with landing points distributed uniformly on the surface.

To make the Monte Carlo sample comparable with the experimental data, the events have been re-weighted according to particular physical assumptions. This study used a power law cosmic ray spectrum with a break at 10^{18} eV (γ= -3.3 for E $< 10^{18}$ eV and γ= -3 for E $> 10^{18}$ eV, motivated by [7]) and with isotropically distributed arrival directions. Two months of data (Los Leones, Bay 4, August-September 2004) have been used, with an estimated total livetime of $T_l = 708000s \pm 10\%$. The expected number of events has been compared with the collected data at different levels: geometry reconstructed (level 1), profile reconstructed (level 2) and after applying physical cuts as described in section 2 (level 3). The result is plotted in Fig. 5 (left) as a

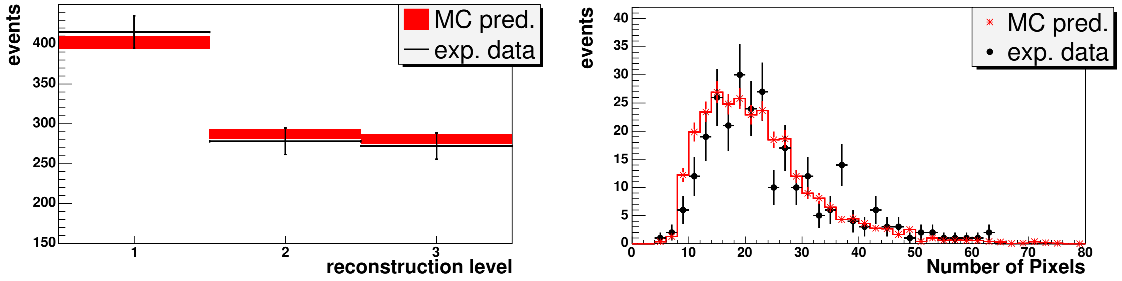

Figure 5. Left: Expected number of events (after weighting) (red boxes) and experimental data (black line) at different reconstruction levels: geometry reconstructed (level 1) profile reconstructed (level 2) and physical cuts as described in section 2 applied (level 3). The Monte Carlo prediction includes the estimated uncertainty on livetime. Only statistical errors are given for data. Right: Predicted and experimental data distribution of pixels used for the longitudinal profile reconstruction.

function of the reconstruction level; the red boxes show the Monte Carlo prediction and the black histogram the experimental data. The uncertainty on the Monte Carlo expectation includes statistical and systematic errors, dominated by the estimated uncertainty on the total livetime; only statistical errors are given for data. The experimental data and prediction agree at each reconstruction level within their uncertainties, demonstrating that the trigger simulation is well understood. As an example of the detailed consistency between data and simulation, the distribution of the number of pixels used for the longitudinal profile reconstruction is shown in Fig. 5 (right) at the last reconstruction level.

4. Conclusions

The performance of the Auger fluorescence detector has been studied using a large number of simulated CORSIKA showers. The energy resolution has been estimated for the case of known fixed shower geometry which provides a realistic estimate for the hybrid operation of the Pierre Auger Observatory. In this case, the energy resolution improves and the number of reconstructible events is larger by a factor 2 with respect to the case of the pure monocular reconstruction. The overall energy resolution depends weakly on the shower energy and remains stable with an average value (RMS) of 9% over the studied range of zenith angles (0° - 60°) and core distances (5 - 60 km). The overall resolution of the atmospheric depth at shower maximum is at the level of 22 g cm^{-2} for iron and 25 g cm^{-2} for protons.

Finally, a comparison between simulation and data has been carried out at trigger level for a large sample of analytical shower profiles (Gaisser-Hillas functions); agreement has been observed at each reconstruction level.

References

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