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Statistical and systematic uncertainties in the event reconstruction and *S*(1000) determination by the Pierre Auger surface detector

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We discuss the statistical and systematic uncertainties in the event reconstruction (core location, and determination of $S(1000)$, i.e., the signal at a distance of 1000 m from the shower core) by the Pierre Auger surface detector for showers with zenith angle less than 60 degrees. The method is based on a maximum likelihood method where the reference lateral distribution function is obtained through the experimental data. We also discuss $S(1000)$ as primary energy estimator.

1. Introduction

The Pierre Auger Observatory, combining fluorescence telescopes with an extensive air shower array of water Cherenkov detectors, is well apt to the study of cosmic rays at the highest energies ($E > 10^{18}$ eV). The use of the two techniques allows the determination of the primary energy improved with respect to former arrays and with no basic dependence on interaction models and hypothesis on the primary composition. The technique is based on the calibration of the energy estimator of the surface detector (SD) through the fluorescence detector data (FD): the SD provides the required statistics thanks to its collecting area and its much larger duty cycle (around 100%). The signal measured at a specific distance from the shower axis, $S(r)$, is well established as an energy estimator for the surface detector: in the Auger observatory r is 1000 m. The accuracy in the determination of such estimator depends on the detector resolution and sampling fluctuations, and on shower fluctuations in the longitudinal development, since the measurement is performed at a single, fixed atmospheric depth. Moreover, the SD energy estimator is not directly measured, but interpolated by a fit to a lateral distribution function (hereafter called LDF). In this paper, we present the results of a study of the accuracies in the event reconstruction and in the determination of the energy estimator by the SD, in view of the measurement of the energy spectrum. With respect to the uncertainties arising from the detector sampling different kinds of shower particles and from the LDF shape, since it is not possible to rely on theoretical predictions, these studies are performed using the experimental data themselves. On the other side, simulations are needed to evaluate the uncertainties due to cascade fluctuations and to justify the choice of $S(1000)$ as energy estimator. After giving in section 2 a brief description of the Pierre Auger array, we will present in section 3 the event reconstruction technique and the systematic and statistical accuracies in the determination of $S(1000)$ and core position. We will discuss in section 4 the effects of shower fluctuations and the stability of $S(1000)$ with respect to such fluctuations.

2. The Pierre Auger surface detector

The surface detector of the Pierre Auger Observatory is extensively described in [1]. We will limit here to describe the characteristics of the detector relevant to the analysis discussed in the following sections.
The water in each Cherenkov detector is viewed with three 9” diameter photomultipliers. Signals are extracted from the anode and from the last dynode (amplified by a factor 40, resulting in a dynode-to-anode ratio of 32) and are then converted, after appropriate calibration (see [2] for a detailed description), in units of vertical equivalent muons (VEM). The VEM is the unit used in the subsequent analysis, both for the LDF and the

reconstruction of $S(1000)$.
A hierarchical trigger sequence (fully described in [3]) is used to identify a cosmic ray event. The lowest level is imposed on each single station, which is fired if the signal satisfies either a 3-fold coincidence of 1.75 VEM on each PMT dynode or a 2-fold coincidence of 13 bins exceeding 0.2 VEM within a 3μs window. The highest level triggers are realized to select physical events, and, for each of them, the stations (≥ 3) which are not due to chance coincidences. The event reconstruction is applied to all the physical events, and among them "quality" events are selected. The "quality" cuts, which will be used in the following analysis, select showers with the highest signal recorded in a tank surrounded by at least five operating ones, and the reconstructed core within a triangle of working stations.
The arrival directions are measured from the relative arrival times of the signals in the selected stations [4], while the core position, (x_c, y_c), and $S(1000)$ are determined from the water Cherenkov signals recorded by each selected station, through a fit to a formula describing the LDF.

3. Event reconstruction: core position and S(1000)

3.1 The reconstruction technique

The reconstruction is based on a maximum likelihood method, in which the signals measured by each station, S_{mea}, are compared with those expected from a lateral distribution function (LDF), S. Determination of the LDF is described in [5] and it is represented by a Nishimura-Kamata-Greisen form:
$S(r) = A\left[\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)\right]^{-\beta}$, with $r_s = 700$ m, $\beta = 2.4 - 0.9 \cdot (\sec\theta - 1)$ and $A = S(1000) \cdot 3.47^{\beta}$.
The likelihood function includes:

(i) a term due to fired stations. This is is given by: $\sum_{\mathrm{fired}} \frac{(S_{\mathrm{mea}} - S)^2}{\sigma^2_{\mathrm{fired}}}$ where $\sigma_{\mathrm{fired}} = 1.06\sqrt{S}$ is the uncertainty in the signal measurement [6]. For fired stations with a saturated anode signal in at least one channel, S_{mea} is the signal deduced using the undershoots on the dynode and anode channels, and due to the coupling capacitors of the bases. In this case $\sigma_{\mathrm{fired}} = 0.08S$ and $\sigma_{\mathrm{fired}} = 0.13S$, for anode undershoot $U_a \leq 1$ ADC channel and $U_a > 1$ ADC channel, respectively.

(ii) a term due to the stations which are below trigger threshold, up to 10 km from a triggered one. The contribution of these stations is described by a Poisson law, with no-detection probability, P, up to 4 VEM: $-2\ln(P) = 2S - 2\ln(1 + S + S^2/2! + S^3/3! + S^4/4!)$

3.2 Uncertainties in the determination of the core position and S(1000)

The statistical accuracies in the measurement of (x_c, y_c) and $S(1000)$ are obtained by fluctuating the signals detected in each station, S_{mea}, adopting a Gaussian law with mean value corresponding to S_{mea} and r.m.s. $\sigma = \sigma_{\mathrm{fired}}$. The reconstruction procedure is then applied to the "fluctuated" event, and repeated 30 times. The widths of the distributions of $S(1000)$, x_c and y_c provide the statistical uncertainty: we show in figure 1 the behavior of $\sigma_{S(1000)}/S(1000)$ vs $S(1000)$, and in figure 2 the distribution of the differences in core location.
The dependence of systematic uncertainties on the determination of (x_c, y_c) and $S(1000)$ arising from the assumed form of the LDF has been investigated. The systematic differences are at the level of about 4% with fluctuations around 4% for either a log-log parabola or the NKG-like form with different β [5], thus showing that the determination of $S(1000)$ is quite stable with respect to the choice of the LDF.

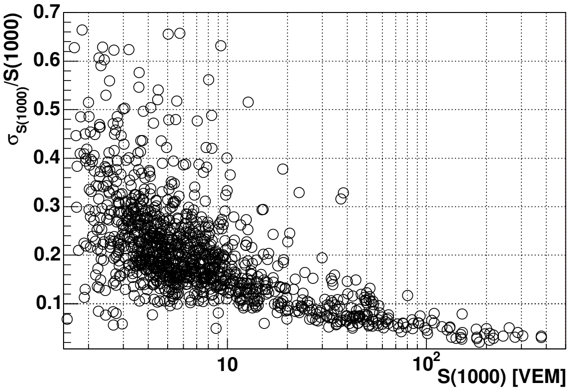

Figure 1. $\sigma_{S(1000)}/S(1000)$ vs $S(1000)$, obtained by the "fluctuation" method (see text).

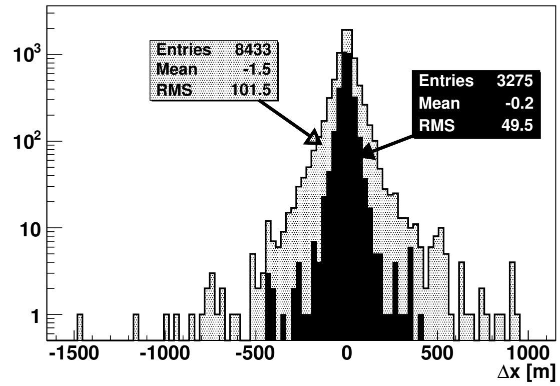

Figure 2. Distribution of differences in core locations Δx: the gray histogram comprises all events, while the black one those with $S(1000) > 30$.

We finally studied the impact of the "quality cuts" on the event reconstruction. To this purpose, we considered only events with the maximum signal detected by a tank surrounded by a full circle of operating detectors, i.e., six. We hence artificially switched off one or more of the fired stations to simulate a shift of the event toward the boundaries, or to simulate the effect of a missing internal station. In any case we preserved the quality criterion of five operating tanks surrounding the one with the maximum signal, and we repeated the reconstruction procedure. We show in figure 3 the ratio between $S(1000)$ after the artificial boundary shift or loss of an internal tank, and the original $S(1000)$: the systematic difference is $\approx 2\%$ while the fluctuations are $\approx 8\%$.

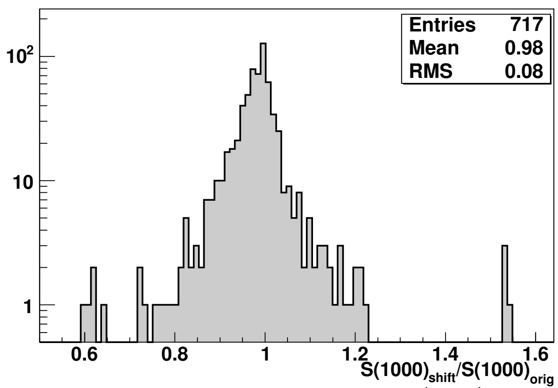

Figure 3. Distribution of the ratio between $S(1000)$ reconstructed after the artificial shift of the event or artificial loss of an internal tank and the original $S(1000)$.

This shows that the "quality cuts" ensure a good uniformity of the reconstruction accuracy with respect to the local position of the event inside the array, or to the possible absence of an internal station.

4. Shower-by-shower fluctuations in $S(1000)$

Intrinsic fluctuations in the process of development of the showers in the atmosphere are a further source of uncertainties in $S(1000)$, different for different primary cosmic ray mass. Such fluctuations were studied by Monte Carlo simulations using the AIRES package [7]. The air showers were simulated for various energies, zenith angles, primary types and interaction models (QGSJET and SIBYLL). The detector response was simulated using a lookup table derived from GEANT4 [8].
Figures 4 and 5 show the r.m.s. of the $S(r)$ distributions, at 10 EeV primary energy, as a function of the zenith angle, for r= 600÷1600 m, for primary protons and irons, respectively, and QGSJET as interaction model. These plots show that the shower-by-shower fluctuations are minimized for $S(1000)$, which is the main reason for choosing it as primary energy estimator.

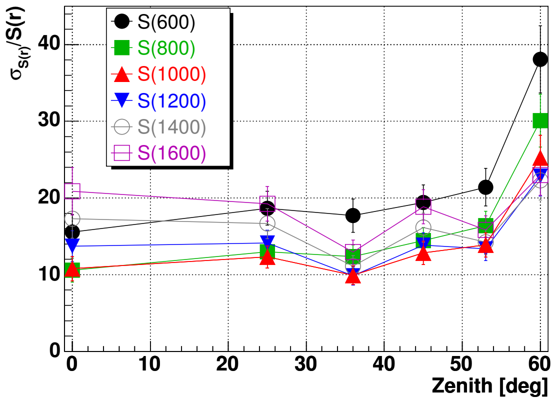

Figure 4. Statistical uncertainty in $S(r)$, for various values of r, vs zenith angle, for 10 EeV primary protons (QGSJET).

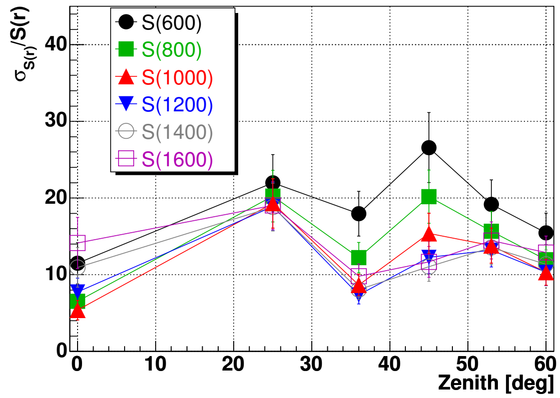

Figure 5. Statistical uncertainty in $S(r)$, for various values of r, vs zenith angle, for 10 EeV primary irons (QGSJET).

Figure 6 shows the statistical uncertainty in $S(1000)$, due to shower development, as a function of $S(1000)$ for proton and iron primaries, at $\theta = 36°$, using QGSJET as interaction model.

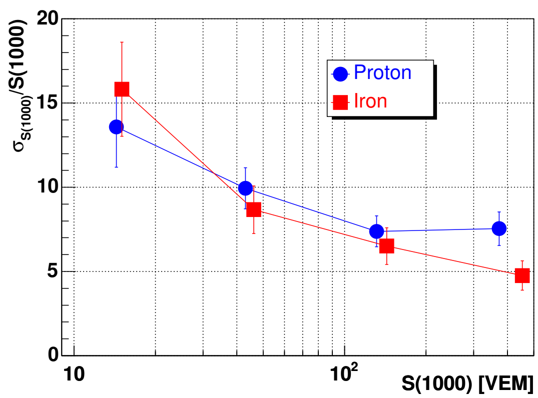

Figure 6. Statistical uncertainty in $S(1000)$ vs $S(1000)$, for proton primaries (circles) and iron ones (squares) (QGSJET).

5. Conclusions

We have shown that for the geometry of the surface detector of the Pierre Auger Observatory the water Cherenkov signal at a distance of 1000 m from the shower core, $S(1000)$, is the best energy estimator, for all primaries and zenith angles.

With respect to the determination of $S(1000)$, the statistical uncertainties at $S(1000) \approx 30$ VEM (corresponding to primary energy around $5 \cdot 10^{18}$ eV) are of the order of 10% (being around 50 m for the core location). The systematic uncertainties due to the assumed LDF form are $< 4\%$, while those due to event sampling within the array or to a missing internal tank give contributions, at most, of the order of the statistical ones. Finally, the fluctuations of $S(1000)$ due to shower development and to event reconstruction are of comparable order.

References

[1] Pierre Auger Collaboration, 29th ICRC, Pune (2005) arg-bertou-X-abs1-he14-oral
[2] M. Aglietta *et al.*, Pierre Auger Collaboration, 29th ICRC, Pune (2005) usa-allison-P-abs1-he14-poster
[3] I. Lhenry-Yvon *et al.*, Pierre Auger Collaboration, 29th ICRC, Pune (2005) usa-bauleo-PM-abs1-he14-poster
[4] Pierre Auger Collaboration, 29th ICRC, Pune (2005) bra-bonifazi-C-abs1-he14-oral
[5] D. Barnhill *et al.*, Pierre Auger Collaboration, 29th ICRC, Pune (2005) usa-bauleo-PM-abs2-he14-poster
[6] T. Yamamoto *et al.*, Pierre Auger Collaboration, Proceedings 28th ICRC (Tsukuba, Japan), (2003) 469
[7] S. Sciutto, AIRES User's Manual available at http://www.fisica.unlp.edu.ar/auger/aires
[8] S. Agostinelli *et al.*, GEANT4 Collaboration, Nucl. Instr. Meth A, 506 (2003) 250