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Reconstruction accuracy of the surface detector array of the Pierre Auger Observatory

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Abstract: The reconstruction of extensive air showers (arrival direction, core position and energy estimation) by the surface detector of the Pierre Auger Observatory is discussed together with the corresponding accuracy. We determine the angular reconstruction accuracy as a function of the station multiplicity by using two different aproaches. We discuss statistical and systematic uncertainties in the determination of the signal at 1000 m from the core, S(1000), which is used to estimate the primary energy.

Introduction

The Pierre Auger Observatory consists of two independent components: the fluorescence detector (FD) and the surface detector (SD) [1]. We have determined the angular resolution of events recorded by the surface detector alone, on an event by event basis, from the zenith (θ) and azimuth (ϕ) uncertainties obtained from the geometrical reconstruction, using the relation described in [2]: $F(\eta) = 1/2\,(V[\theta] + \sin^2(\theta)\,V[\phi])$, where η is the space-angle, and $V[\theta]$ and $V[\phi]$ are the variance of θ and ϕ respectively. We define the angular resolution (AR) as the angular radius that would contain 68% of showers coming from a point source, $AR = 1.5\,\sqrt{F(\eta)}$. We checked the angular resolution using the redundant information given by a sub-array composed by adjacent detectors.

The parameter used to infer the energy of the surface detector events ($S(1000)$) is studied and its systematic and statistical errors are determined. The event-by-event error estimation is checked with full Monte Carlo simulations . The unavoidable fluctuations in this parameter caused by fluctuations in the shower development is evaluated with simulations for different primary assumptions.

Angular Resolution

The arrival direction of a SD event is determined by fitting the arrival time of the first particle in each station to a shower front model. The precision achieved in the arrival direction depends, on the clock precision of the detector and on the fluctuations in the first particle arrival time. In [3] an empirical model has been developed to determine the uncertainty in the time measurement of each individual detector participating in the event.

The model of the shower front used in the minimization procedure, be it spherical, parabolic, or even planar also influences the uncertainty in the arrival direction determination, but not as much as the time measurement precision. It has been shown in [3] that a parabolic model for the shower front adequately describes the data.

On a event by event basis

Given the two inputs: a model for the time variance and a model for the shower front, the angular resolution can be calculated on an event by event basis out of a minimization procedure. In Fig. 1, we show our angular resolution as a function of the zenith angle for various station multiplicities (circles: 3 stations, squares: 4 stations, up triangles: 5

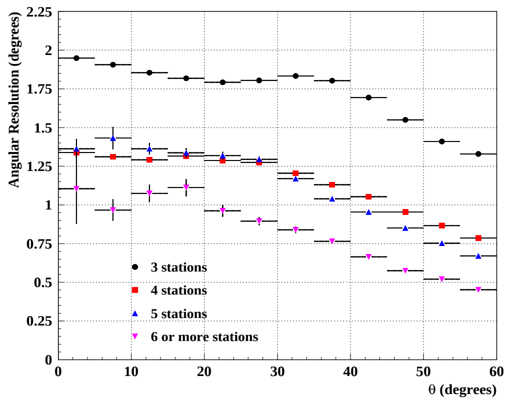

Figure 1: Angular resolution (AR) for the SD as a function of the zenith angle (θ). The AR is plotted for various station multiplicities.

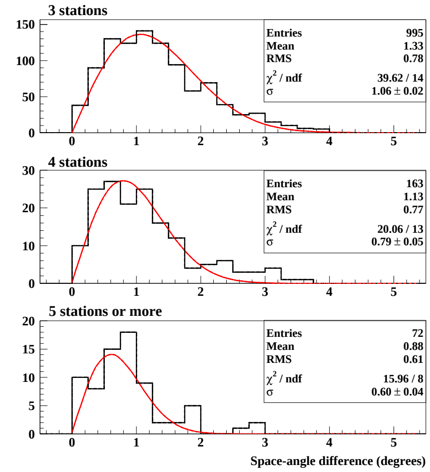

Figure 2: Space-angle difference between two SD estimates of the event geometry for different multiplicities (see text for more details).

stations, down triangles: 6 stations or more). The data used to build this plot spans from January/2004 to March/2007.

As it can be seen, the angular resolution is better than 2° in the worst case of vertical showers with only 3 stations hit. This value improves significantly for 4 or 5 stations[1]. For 6 or more stations, which corresponds to events with energies above 10 EeV, the angular resolution is in all cases better than about 1°.

Using station pairs

A new sub-array of pairs has been recently deployed as a part of the Surface Detector array. These are adjacent detectors located $\sim$ 11 m apart, and therefore are sampling the same region of the shower front. To do this analysis, events with at least three pairs are selected. The reconstruction is then performed twice, each time using the time information of one of the tanks in each pair. This provide two quasi-independent estimates of the geometry. In Fig. 2 we show the space-angle difference between these two estimates for showers with 3, 4, and 5 or more stations.

The distributions are then fitted to the adjusted Gaussian resolution function ($dp \propto e^{-\eta^2/2\sigma^2}\ d(\cos(\eta))\ d\eta$, where η is the angle between the two reconstructions of the same shower) to obtain σ. The angular resolution (68% contour), which is given by 1.5 times σ, is in agreement with the one obtained on a event by event basis.

Energy Estimator

The surface detector only samples the properties of an air shower at a limited number of points at different distances from the shower axis (r). An observable has to be then defined to estimate the shower size. To avoid the large fluctuations in the signal integrated over all distances caused by fluctuations in the shower development, Hillas [4] proposed to use the signal at a given distance ($S(r)$) to classify the size of the shower. In Fig. 3 we show the predictions from Monte Carlo simulations of the magnitude of the fluctuations in $S(r = 1000)$ as a function of zenith angle. The relative fluctuations are found to be independent of energy and its magnitude is $\sim$ 10% for most of the cases studied.

The experimental error in the estimation of the signal size at a given core distance depends on the spacing of the array. In [5] it has been shown that for the Auger array spacing the

1. For 4 and 5 stations the AR is very similar because in the fitting procedure they have the same number of degrees of freedom.

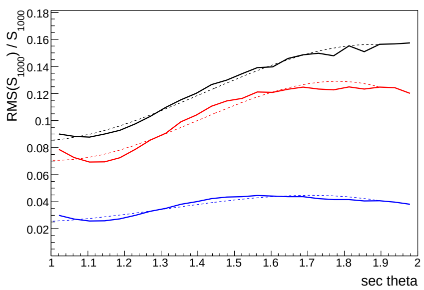

Figure 3: Relative spread due to shower to shower fluctuations for different compositions (blue-iron, red-proton, black-mixed composition).

optimum distance (r_{opt}) to minimize this experimental error is ~1000 m. Therefore, the observable that we use to relate to the primary energy will be the signal size at 1000 m ($S(1000)$)[2]. However, it should be noted that r_{opt} fluctuates from event to event and increases to larger core distances ($\sim$ 1500 m) when there are saturated stations [5].

To estimate $S(1000)$ it is necessary to adopt a lateral distribution function (LDF) that describes the fall-off of the signal size with the distance to the shower axis. The function used here is a modified NKG function given by: $S(r) = S(1000)\left(\frac{r}{1000}\right)^{-\beta}\left(\frac{r+700}{1700}\right)^{-\beta}$, where r is the distance to the shower axis in meters, $S(r)$ is the signal size at a core distance r, $S(1000)$ is the size parameter of the shower, and β is called the slope of the LDF.

S(1000) uncertainties

The signal sizes in each station are then used to estimate the core location and $S(1000)$, with β being a fixed parameter. The *fitting* error in $S(1000)$ is a consequence of the uncertainty of the observed signal size largely due to the finite dimension of the detectors. This will be the statistical error in $S(1000)$ ($\sigma^{stat}_{S(1000)}$). The uncertainty in the signal sizes has been measured directly using pairs of stations located close to each other in the field [6].

The second source of error in $S(1000)$ is a systematic ($\sigma^{sys}_{S(1000)}$) arising from the lack of knowledge of the true LDF shape for a particular event. If the r_{opt} of a given event is close to 1000 m, the fitted $S(1000)$ is independent of the value of β assumed [5]. When it is not, fluctuations in the event by event β give rise to a systematic error. The value of β to be used in the reconstruction has been estimated empirically: in a small subset of events ($S(1000) > 20$ VEM and having more than 5 stations) the β is left as a free parameter as well. We then parameterize the fitted values of β as a function of zenith angle and $S(1000)$. The deviation from this parameterization is calculated for each event and the RMS (σ_β) parameterized as a function of $S(1000)$ (no dependence on zenith angle has been found). The result is the following: $\sigma_\beta(S(1000)) = 0.71 \times \exp(-0.976\ \log(S(1000)))$. We then repeat N times the reconstruction of each event, fixing β to values sampled from a Gaussian distribution centered around the prediction with the sigma given above. The RMS of the fitted $S(1000)$ from these set of fits is then the systematic error of $S(1000)$ ($\sigma^{sys}_{S(1000)}$).

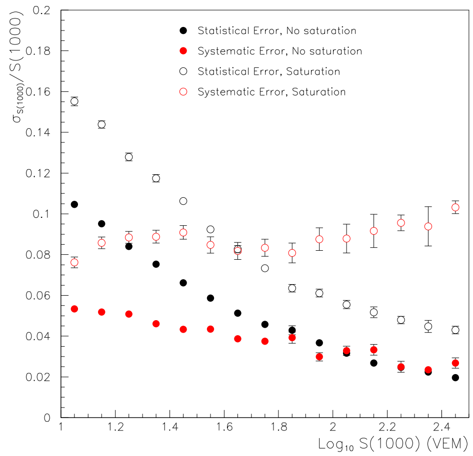

Figure 4: The average systematic and statistical error in S(1000) as a function of *log* $S(1000)$. The data has been divided in two sets (events with-without stations saturated).

In Fig. 4 we show the average systematic and statistical error of $S(1000)$ as a function of $\log(S(1000))$. The data has been divided in two sets: events with (without) saturated sta-

2. $S(1000)$ is measured in units of VEM, i.e. the signal produced by a vertical centered muon.

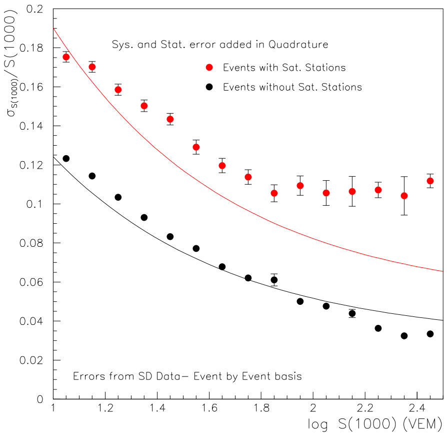

Figure 5: Total error in $S(1000)$ calculated on an event by event basis from the data. The data is separated in two sets: events with (without) saturated stations. The lines correspond to the predictions from full MC calculations (see text for details)

tions. Two features are clearly seen: a) the error in events with saturated stations is systematically 5% larger, b) $\sigma^{stat}_{S(1000)}$ dominates the error budget for $S(1000)$ <40 VEM. No dependence of $\sigma^{sys}_{S(1000)}$ or $\sigma^{stat}_{S(1000)}$ on zenith angle has been found.

Using Full Monte Carlo Simulations

To benchmark our error estimation we have created a library of Corsika showers for proton primaries, zenith angles $\theta=$ 0-12-25-36-45-60 degrees and energies $\log_{10} E(eV)$=17.8-18.0-18.2-18.4-18.6-19.0-19.5-20.0. For each Corsika shower, we calculate the *true* $S(1000)$ and it is then used to generate 10 (25) events (depending on the energy) with random core positions.

The reconstruction procedure used for the data is then applied to the simulations. For each zenith angle and energy we fit the distribution of $\log\left(\frac{S(1000)^{rec}}{S(1000)^{true}}\right)$ to a Gaussian function. The mean value and sigma are then parameterized as a function of $S(1000)^{true}$. No zenith angle dependence has been found. A bias in the reconstructed $S(1000)$ is only found for $S(1000) < 10$ VEM. The sigma of this distribution is the quadrature combination of the statistical and systematic error in $S(1000)$. In Fig. 5 we show the comparison of the sigma of these distributions with the average total error obtained on an event by event basis. The data is separated in two sets: events with (without) saturated stations. The circles correspond to the total error obtained on a event by event basis, the lines are the predictions from full Monte Carlo simulations. The agreement is excellent except for a slight overestimation of the error ($\sim$4%) for saturated events at large energies.

Conclusions

The angular resolution of the surface detector was determined experimentally, checked using the pairs data set and found to be better than 2° for 3-fold events ($E < 4$ EeV), better than 1.2° for 4-folds and 5-folds events ($3 < E < 10$ EeV) and better than 0.9° for higher multiplicity events ($E > 10$ EeV).

The error of the parameter used to infer the energy of the surface detector events ($S(1000)$) has been determined experimentally, checked using full Monte Carlo simulations and found to be better than 8% (12%) at the highest energies for events with (without) saturated stations. At high energies, the fluctuations in $S(1000)$ are dominated by fluctuations in the shower development.

References

[1] J. Abraham [Pierre Auger Collaboration], NIM 523 (2004) 50.

[2] C. Bonifazi [Pierre Auger Collaboration], Proc. 29^{th} ICRC, Pune (2005), **7**, 17-20.

[3] C. Bonifazi et al., submitted to Astropart. Phys. [arXiv:astro-ph 07051856]

[4] A. M. Hillas et al., Acta Physica Academiae Scietiarum Hungaricae 29, Suppl 3, 533.

[5] D. Newton et al., Astropart. Phys. 26 (2007) 414-419.

[6] M. Ave et al, NIM 578 (2007), 180-184