29th International Cosmic Ray Conference Pune (2005) 7, 99–102

Top-Down Reconstruction of Ultrahigh Energy Air Showers

F. Schüssler[a], J. Blümer[a,b], R. Engel[b] and M. Unger[b]

(a) University of Karlsruhe, Institut für exp. Kernphysik Postfach 6980 76128 Karlsruhe, Germany

(b) Forschungszentrum Karlsruhe, Institut für Kernphysik, Postfach 3640, 76021 Karlsruhe, Germany

Presenter: R. Engel (ralph.engel@ik.fzk.de), ger-engel-R-abs1-he14-poster

Based on the new air shower simulation tool CONEX, we evaluate the potential of a top-down reconstruction of ultrahigh energy air showers measured with the fluorescence telescopes of the Pierre Auger Observatory. A large number of simulated longitudinal shower profiles are passed to a complete fluorescence simulation chain, consisting of the production of fluorescence and Cherenkov light, light propagation in the atmosphere and a detailed simulation of the detector response including realistic resolutions, fluctuations and efficiencies. Using χ^2 test statistics, the simulated detector output is then directly compared to measured fluorescence signals. To test this method, it is applied to signals from simulated air showers and the reconstructed shower parameters are compared with the true ones.

1. Introduction

Due to the great importance of air shower measurements at the very end of the cosmic ray spectrum for the theoretical understanding of the highest energy phenomena in our universe, it is vital to be able to reconstruct these rare events as accurately and completely as possible.

In a conventional reconstruction procedure of fluorescence measurements as developed by the pioneering experiment Fly's Eye [1], first the event geometry is reconstructed and in a next step the shower profile is determined. Only subsets of the complete event information are used in each reconstruction step and correlations between reconstructed geometry and shower profile are disregarded.

The presented top-down reconstruction procedure takes into account the whole information available after the detection of an air shower by a single fluorescence telescope, namely the full ADC-traces of each triggered pixel (ADC-counts as function of time), the information about the atmospheric conditions at the time of measurement (atmospheric profile, attenuation and scattering parameters) and the knowledge about the detector itself, i.e. pointing directions and calibration constants of each camera pixel.

2. Top-Down reconstruction procedure

Top-down approaches use Monte Carlo simulations to derive the parameters of the air shower and its primary particle. Based on rough first estimates of the shower geometry and energy, provided usually by the standard algorithms, a large number of extensive air showers is simulated in the phase space around the estimated shower parameters and the response of the fluorescence detector to these simulated signals is derived. Statistical tests are then employed in order to find the most probable values of the parameters of the air shower and its primary particle including their errors and correlations.

In order to allow a sufficiently accurate reconstruction of the shower parameters, the simulated showers have to cover a wide range of phase space as close as possible. The ranges adopted here can be found in table 1 and equal about $\pm 3\sigma$ of the obtained resolution.

The potential of this method is evaluated by applying it to simulated showers inspired by the most energetic event detected by the Pierre Auger Observatory so far [2].

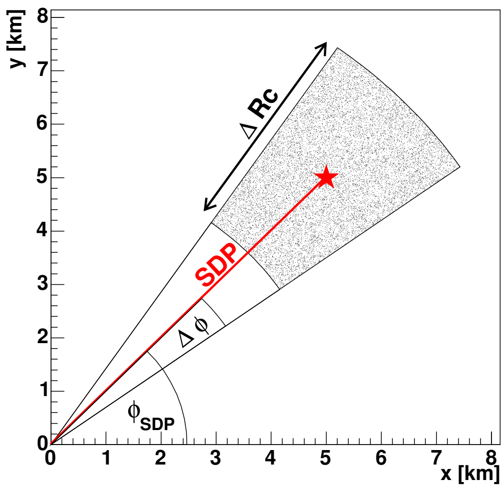

Figure 1. Construction of core position range around the first guess (red star) with the fluorescence detector situated at the origin.

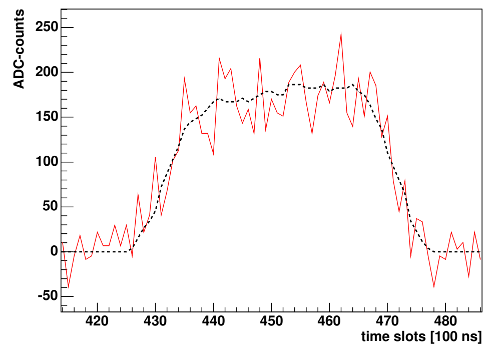

Figure 2. Example of an ADC-trace of a single camera pixel after the trigger simulation (red solid line) in comparison to the original trace (black dashed line).

Air shower simulation: CONEX [3] is applied to simulate longitudinal energy deposit profiles of extensive air showers. It combines both MC techniques and numerical solutions of the underlying cascade equations in order to reduce the needed computing time considerably. In this first simulation step, QGSJET01 [4] has been selected as high energy interaction model and air showers were produced with an energy spectrum constant in $\log_{10}(E)$. All other shower parameters, e.g. $X_{\max}$, were obtained naturally during the shower simulation.

Fluorescence light simulation: FDSim [5] has been used for the simulation of emission and propagation of fluorescence and Cherenkov light produced by these showers.

The distance between shower core and detector, $R_{\rm core}$, corresponding to the core position inside the shower-detector-plane (SDP), has been chosen while taking into account possible variations of the SDP-direction itself, described through the angle $\phi_{\rm SDP}$ with respect to the Auger site coordinate system (see figure 1).
In order to completely define the position of the shower in the atmosphere, the azimuth and zenith angle, ϕ and θ respectively, have also been chosen randomly in a fixed range around the first estimation given by the standard reconstruction.

Parameter	Range
Energy	$\pm$ 25 %
$R_{\rm core}$	$\pm$ 2 km
$\phi_{\rm SDP}$	$\pm\ 1.5^\circ$
θ	$\pm\ 3^\circ$
ϕ	$\pm\ 3^\circ$

Table 1. Parameter ranges used for the shower simulations.

Detector simulation: As first step of the detector simulation, signal fluctuations based on background light and readout electronics are simulated. For the first one, a number of photons derived from night sky background measurements at the Auger site are distributed over the camera surface. The total number of photons at each pixel is then converted into photoelectrons and Poissonian fluctuations are applied, before simulating the noise caused by the electronics itself.

Using measured calibration constants, the photoelectrons are then translated into ADC-counts and passed through the same trigger algorithms as implemented in the actual data taking of the Auger detectors. The

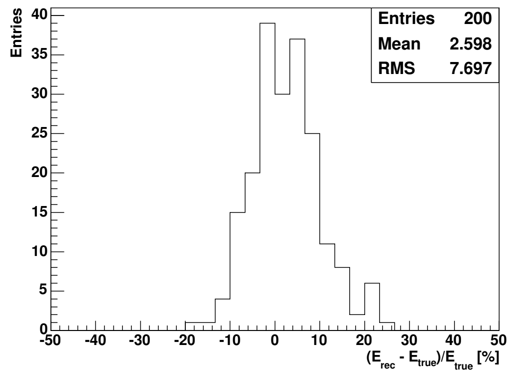

Figure 3. Primary energy resolution for the top-down reconstruction of mono fluorescence events (preliminary).

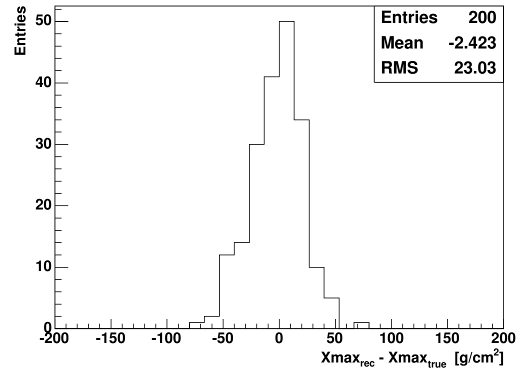

Figure 4. Depth at shower maximum resolution for the top-down reconstruction of mono fluorescence events (preliminary).

simulated output is translated into the Auger DAQ format and stored together with the original ADC-traces carrying no detector noise (see figure 2).

Comparison: After extraction of the ADC-traces of all triggered pixels, a χ^2-value and corresponding probability $P(\chi^2_{\rm S}, \mathrm{ndof})$ is assigned to each MC shower through comparison with the measured traces:

$$\chi^2_{\rm S} = \sum_{\text{pixel } i} \sum_{\text{time } t} \frac{(F_{\rm D}(i,t) - F_{\rm MC}(i,t))^2}{\sigma^2_{\rm B}(i) + \sigma^2_{\rm MC}(i,t)} \tag{1}$$

$$P(\chi^2_{\rm S}, \mathrm{ndof}) = \int_{\chi^2_{\rm S}}^{\infty} f_{\rm ndof}(\chi^2)\, d\chi^2 \tag{2}$$

$F_{\rm D}(i,t)$ and $F_{\rm MC}(i,t)$ denote the ADC-signal of the data and MC shower, respectively. $f_{\rm ndof}(\chi^2)$ stands for the χ^2 probability density function. In order to account for possible boundary effects of the pulses, the integration time window of each camera pixel has been chosen to be 50% larger than the reconstructed ADC-pulse. The error related to the noise background of the measurement can be estimated from the data itself through determining the RMS of the background fluctuations in a region outside the pulse: $\sigma_{\rm B}(i) = \sqrt{\mathrm{RMS}_{\rm noise}}$. Using the MC ADC-trace without noise fluctuations, the signal error is caused only by Poissonian fluctuations of the photoelectrons and can be written as $\sigma_{\rm MC}(i,t) = \sqrt{k_i \cdot F_{\rm MC}(i,t)}$, where k_i denotes the conversion factor between ADC-counts and photoelectrons and has been derived from calibration measurements.

The *top-down reconstruction result* is given by the shower with minimal $\chi^2_{\rm S}$ and its corresponding parameters. The related uncertainties are determined by the maximal deviations of the parameters obtained from all showers falling inside $\chi^2_{\rm min} + 1$.

3. Preliminary results

Based on this MC study, namely the top-down reconstruction of simulated air showers, first preliminary results of the presented method can be derived. Only simulated data from one fluorescence detector has been used in this *monocular reconstruction*. All shower parameters have been varied within the boundaries given in table 1 and determined during the reconstruction process. No additional quality cuts have been used. As example the

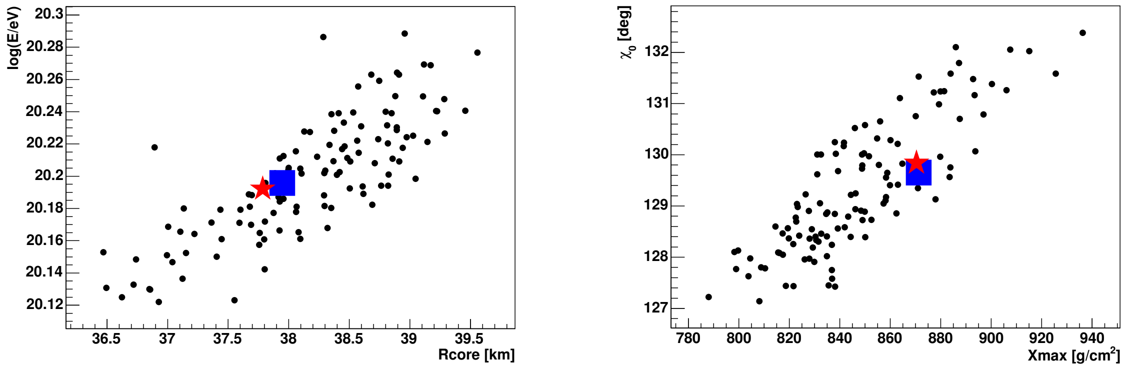

Figure 5. Reconstruction example of one event: Correlation between reconstructed energy and distance between detector and shower core (left panel) and correlation between the reconstructed angle between shower axis and ground plane χ_0 inside the shower detector plane and the position of shower maximum $X_{\max}$ (right panel). The *reconstruction results* are shown as blue squares, the true values are given as red stars. In addition all MC showers having a probability $P > 5$ % are shown.

obtained energy resolution (RMS $\approx$ 8 %) and the corresponding residual of the depth at shower maximum (RMS $\approx 23\ \mathrm{g/cm^2}$) are shown in figure 3 and 4, respectively for 200 reconstructed showers. Simultaneous reconstruction of the shower geometry results in $\mathrm{RMS}(\theta) \approx \mathrm{RMS}(\phi) \approx 1°$ and $\mathrm{RMS}(R_{\mathrm{core}}) \approx 0.6$ km.

Another possible application of top-down reconstruction algorithms is the systematic study of the correlation between parameter uncertainties. Using the reconstruction of a single shower, one can, for example, check the correlation between reconstructed energy and core distance, or the correlation between shower angle χ_0 and depth at shower maximum $X_{\max}$ as demonstrated in figure 5. Only MC showers having a probability $P(\chi^2_{\mathrm{S}}, \mathrm{ndof})$ greater than 5% are shown.

Although based only on monocular observations of air showers, the presented top-down reconstruction method provides superior resolution and realistic, asymmetric error estimates in comparison to standard reconstruction algorithms, see for example [6]. Its application will nevertheless be limited to some of the highest energy events due to the computational requirements needed to perform the calculations.

References

[1] R. M. Baltrusaitis et al., Fly's Eye Collab., *Nucl. Instr. Meth.* A240 (1985) 410.

[2] M. Ave et al., Pierre Auger Collab., these proceedings, usa-ave-pernas-M-abs1-he14-oral.

[3] S. Ostapchenko et al., these proceedings, ger-ostapchenko-S-abs2-he14-poster; T. Pierog et al., astro-ph/0411260.

[4] N.N. Kalmykov, S.S. Ostapchenko, and A.I. Pavlov, *Nucl. Phys. B (Proc. Suppl.)* 52B (1997) 17.

[5] L. Prado Jr. et al., *Nucl. Instr. Meth.* A545 (2005) 632.

[6] L. Perrone et al., Pierre Auger Collab., these proceedings, ger-kampert-K-abs3-he14-poster.