29th International Cosmic Ray Conference Pune (2005) **7**, 21–24

Lateral width of shower image in the Auger fluorescence detector

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The impact of the lateral distribution of light in extensive air showers on the detection and reconstruction of shower profiles is investigated for the Auger fluorescence telescopes. Based on three-dimensional simulations, the capability of the Auger telescopes to measure the lateral distribution of light is evaluated. The ability to infer the actual lateral distribution is confirmed by the comparison of detailed simulations with real data. The contribution of pixels located far from the axis of the shower image is calculated and the accepted signal is rescaled in order to reconstruct a correct shower profile. The analysis presented here shows that: (a) the Auger telescopes are able to observe the lateral distribution of showers and (b) the energy corrections to account for the signal in outlying pixels can exceed 10%, depending on shower geometry.

1. Introduction

The Pierre Auger Observatory is a hybrid detector based on fluorescence telescopes and water Cerenkov tanks [1]. The basic configuration of the Auger telescopes is a Schmidt camera consisting of a 1.1 m radius aperture (including a ring of corrector lenses), and a spherical mirror with a $30° \times 30°$ of field of view. The fluorescence light is detected by an array of 440 photomultipliers, each with 1.5° diameter field of view. The signal is sampled in time slots of 100 ns.

The amount of fluorescence light produced by a shower particle is proportional to the energy it deposits in air via ionization losses. As can be seen in reference [2], the energy deposited by the particles in an air shower has a wide lateral distribution. According to that work, electrons and positrons at distances between 100 and 1000 meters from the shower axis account for 15 to 20% of the energy released in air by a shower.

Figure 1 shows examples of two events measured by the Auger telescopes. Both events had reconstructed energies of 2.2 EeV. The shower illustrated in the left panel landed with a core 10.5 km from the telescope while the shower illustrated in the right panel landed only 4.5 km away. Note the difference in lateral spread of the signal in these showers.

In this paper, we investigate how the Pierre Auger telescopes detect the lateral distribution of particles in the shower. We compare the simulated lateral spread of light on the camera with that seen in real events. Finally, a correction is proposed for the reconstructed shower energy, to take account of the fraction of light falling into pixels located far from the axis of the image.

2. Detection of the Lateral Distribution by the Auger Telescopes

A three-dimensional shower simulation program CORSIKA [3] was used to evaluate the lateral distribution of particles in the shower and consequently the lateral spread of the signal on the camera. The energy deposited by particles in the atmosphere as given by CORSIKA can be converted to fluorescence photons and propagated to the telescope aperture.

The telescope simulation and the shower reconstruction have been done using the official Auger collaboration programs described in references [4, 5].

In order to investigate the capability of the Auger telescopes to measure the lateral distribution of showers, we

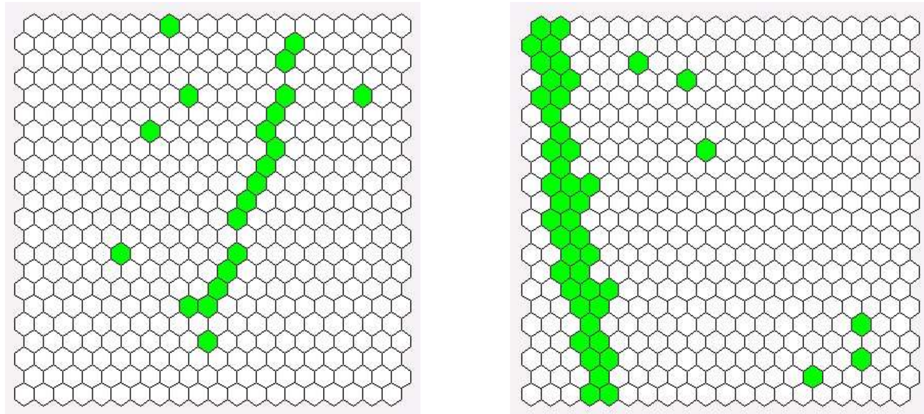

Figure 1. Image of two showers in the photomultiplier camera. The reconstructed energy of both showers is 2.2 EeV. The shower on the left had a core 10.5 km from the telescope, while that on the right landed 4.5 km away. Note the number of pixels and the lateral spread in the image in each shower.

have simulated two sets of 100 vertical showers initiated by 10^{19} eV protons. One set was simulated with the three-dimensional approach and the other with a one-dimensional simulation using a Gaisser-Hillas function for the longitudinal profile.

Two parameters have been investigated in this study: the number of triggered pixels and the ζ angle. The ζ angle is the radius of a circle (measured in degrees) on the photomultiplier camera which maximizes the signal to noise ratio, S/N for collected light. The distribution of triggered pixels on the camera allows us to determine the main track of the shower by fitting a line to the hit pixels. Signal from a pixel is included in the measured light flux if the pixel center lies within an angle ζ from the track axis. The value of ζ is varied to search for a maximum S/N. After the search, ζ is set to a fixed value for the entire track.

Figure 2 shows the expectation for the number of triggered pixels and ζ, obtained for one and three-dimensional simulations as a function of the distance between the telescope and the core position of the shower. Figure 2 shows that for cores closer than 10 km the lateral distribution of the particles in the shower produces a measurable and important spread of the signal on the photomultiplier camera at primary energies of 10^{19} eV. Real data are also shown in the figures, from showers measured to have energy between $10^{18.5}$ and $10^{19.5}$ eV, and these data follow the expectation from the three-dimensional simulation. This shows the capability of the telescopes to measure the lateral distribution of the signal produced by showers.

3. Influence of the Lateral Distribution in the Energy Reconstruction

The primary energy of the shower is calculated based on the amount of fluorescence light recorded by the fluorescence telescope. The standard reconstruction procedure sums the measured charge in each time slot (for pixels within the radius ζ) and converts it to the number of photons at the telescope aperture using calibration constants.

However, this method is most suitable for distant showers where the light collected within the radius ζ corresponds to about 100% of the total signal. Some differences between the signal within ζ and the total signal produced by a shower may exist for nearby showers.

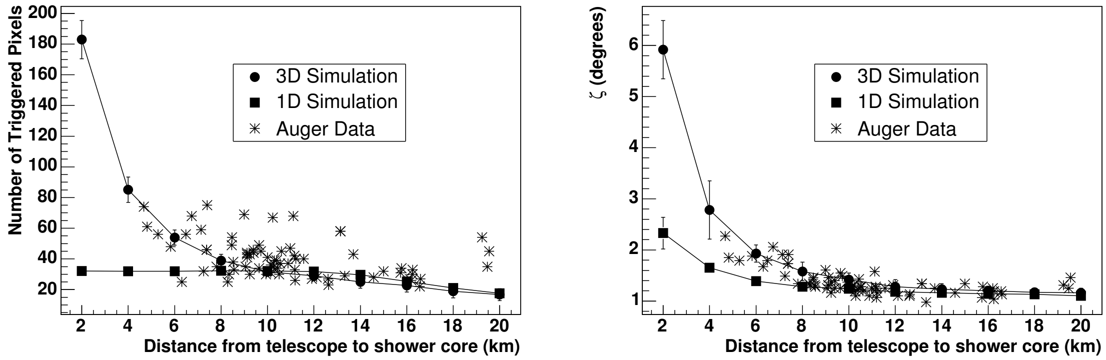

Figure 2. Number of pixels and ζ as a function of the distance between the telescope and the shower core.

As can be seen in reference [6], the fraction of energy deposited $F(r)$ within a distance r, measured in Molière units, can be well parameterized as a function of an effective shower age parameter only.

We have used this parameterization to calculate the total signal produced by the passage of the shower, which may be distributed among several neighboring detector pixels. For a given geometry of the shower, we find the collected signal $L_\zeta(t)$ within the angular distance ζ at each time interval. Then, for the given ζ and the detector-to-shower distance R_0, the effective radius around the shower axis for which the produced signal will be accounted for in the standard energy reconstruction is given by $r_0 = R_0 \tan(\zeta)$.

The fraction of energy deposited in air within r_0, and therefore the amount of fluorescence light, can be calculated according to reference [6]. Finally, the signal outside r_0 can be considered in the energy reconstruction by rescaling $L_\zeta(t)$ according to the formula $L_{total}(t) = L_\zeta(t)/F(r_0)$.

Figure 3 shows four events measured by the Auger telescopes to which this procedure has been applied. It is seen that for Event1 $F(r_0)$ changes from 89% for a distance to the shower of $R_0 = 7.0$ km to 87% for $R_0 = 6.0$ km. Accepting only a fraction of the signal contained within ζ directly influences the reconstructed primary energy of the shower. In Table 1 we present the influence of the correction on the Gaisser-Hillas fit to the reconstructed number of particles in the showers. It is seen that this correction changes both the number of particles at the shower maximum and the position of the shower maximum. These changes lead to different estimates of primary energy. In the last column of Table 1 the relative differences $k_E = (E_0^{total} - E_0^\zeta)/E_0^\zeta$ are listed. One sees that k_E is always positive and decreases from 14% for a distance to shower maximum of R_0=6.5 km to 2% for R_0=23 km.

4. Conclusion

The Pierre Auger fluorescence telescopes are able to detect the lateral distribution of particles in close-by showers and an energy correction must be applied due to this effect. The correction can exceed 10%, as shown in Table 1, depending on the geometry of the shower.

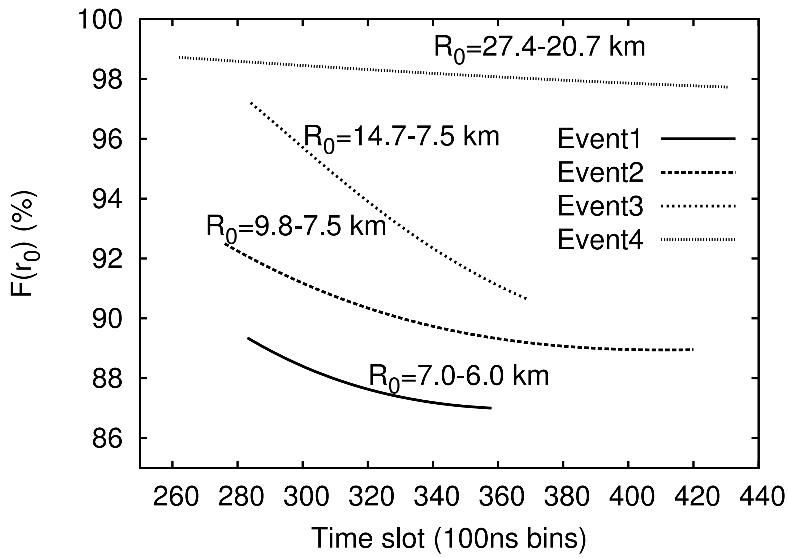

Figure 3. Fraction of light collected within the angle ζ versus time for four events measured by the Auger telescopes.

Table 1. Comparison of Gaisser-Hillas function parameters based on the $L_{total}(t)$ and $L_\zeta(t)$ light profiles and their influence on primary energy.

Event	R_0 (km)	N^ζ_{max} (10^9)	N^{total}_{max} (10^9)	X^ζ_{max} (g/cm^2)	X^{total}_{max} (g/cm^2)	E^ζ_0 (EeV)	E^{total}_0 (EeV)	k_E (%)
Event1	6.4	0.93	1.06	701	706	1.370	1.562	14
Event2	8	6.57	6.88	759	767	9.853	10.40	6
Event3	11	2.12	2.19	637	642	2.950	3.100	5
Event4	23	12.85	13.10	752	753	19.20	19.57	2

5. Acknowledgments

This work was partially supported by the Polish Committee for Scientific Research under grants No. PBZ KBN 054/P03/2001 and 2P03B 11024, in Germany by the DAAD under grant No. PPP 323 and in Brazil by CNPq and FAPESP.

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