Auger-South Hybrid Sensitivity to Highly Inclined Hadron-Induced Air-Showers: Mass Composition at High Energy

M. Ave [1], C. K. Guérard[2], L. Perrone[3], R.A. Vazquez[4] and E.Zas[4]
(1) Center for Cosmological Physics, University of Chicago, 933 S. Ellis Av, Chicago 60637, USA
(2) IEKP, Universität Karlsruhe, Postfach 3640,D-76021 Karlsruhe, Germany
(3) Fachbereich Physik, Universität Wuppertal, 42097 Wuppertal, Germany
(4) Departamento de Fisica de Particulas, Campus Sur s/n, Universidad de Santiago de Compostela, E-15706 Santiago de Compostela, Spain

Abstract

The Auger Observatory aims at the detection of Ultra-High-Energy Cosmic-Rays using atmospheric fluorescence telescopes over-viewing a 3000 km^2 array of water Cherenkov tanks, a mini prototype of which has been successfully taking data since 12/2001 in the province of Mendoza, Argentina. In this paper we present a Monte Carlo calculation of the hybrid sensitivity of the Auger-South Observatory to highly inclined hadron-induced air-showers, and show that such showers can play an important role to extract the mass composition of the highest energy cosmic rays.

1. Introduction and Outline of the Method

Efforts to understand the origin of cosmic rays at energies above 100 TeV are greatly hampered by our lack of knowledge of the mass distribution in the incoming cosmic ray beam. While there is a common assumption that protons dominate at energies above 10^{18} eV, hard experimental evidence is lacking.

The number of muons at ground level can be used to determine the mass distribution of the cosmic ray beam, as heavier primaries are more effective producing muons. However, we have to face the experimental challenge of counting muons using water Cherenkov detectors. Two approaches can be used: (1) We can use the FADC traces of the recorded events and try to separate the muonic from the electromagnetic component. (2) The approach proposed in this work: To use inclined showers (with zenith angles larger than 60°). Inclined showers would not be very different from vertical showers except for the fact that they develop in the upper part of the atmosphere. As a result the electromagnetic part of the shower, produced mainly from π° decay, is mostly absorbed well before the shower front reaches ground level. However, the muon front propagates through the atmosphere mixed with an electromagnetic halo coming from muon

pp. 563–566

Bremsstrahlung, pair production and muon decays. This halo is continuously generated and represents less than 15% of the signal in a Cherenkov tank as long as one is sufficiently far away from the core (a few tens of meters).

The spatial distribution of muons at ground is related to the distance travelled by the muons from their production points to ground. These distances vary slightly for different primaries. As an example, for 70° zenith angle showers it is 30 (33) km for proton (iron) primaries. It is explicitly shown in [1] that the muon distributions at ground level are hardly different in shape for iron and proton primaries.

From the previous discussion, it becomes clear that the signal recorded by water Cherenkov tanks at any given position relative to shower core is approximately proportional to the number of muons in the shower. Unfortunately, in order to reconstruct the energy of an inclined event we have to make an assumption on primary composition. Here is where the hybrid capability of the Auger Observatory takes a key role. The energy can be obtained using the fluorescence technique with only a small systematic uncertainty due to the unknown mass. Moreover, knowledge of the position of the shower maximum (X_m), sensitive to primary composition as well, can also be used.

Fig. 1 shows the correlation between X_m and the number of muons (N_μ) obtained with simulations for a zenith angle of 66° and a primary energy of 10^{19} eV. We have used a library of showers generated by S. Sciutto using the computing facilities in Fermilab. The Monte Carlo code used is AIRES [2]. The separation between proton and iron primaries is clear. The correlation between X_m and N_μ is small, as expected, since the fluctuation in N_μ is related to the fluctuations in the number of charged pions produced in the first interactions which have little effect on the position of the shower maximum.

In the next section, a calculation of the predicted number of hybrid inclined hadron initiated showers is presented.

2. Calculation of the Hybrid Rate

It is shown in [3] that inclined showers with cores inside the array, energies above 10 EeV and zenith angles larger than 60° have a trigger efficiency close to 100 %. The number of hybrid inclined showers is then determined by the fluorescence detection efficiency.

Fluorescence telescopes detect the optical fluorescence from the ionization of N_2 molecules when cosmic rays shoot through the atmosphere. The fluorescence yield has proven to be proportional to charged-particle energy deposit [4]. It is isotropic and, depending on air density and temperature, can vary from 3 to 5.6 photons/m/charged-particle with wavelengths ranging from $\sim$ 280 to 450 nm. The fluorescence technique has the great advantage that fluorescence light can be detected very far away from its point of emission. The question then

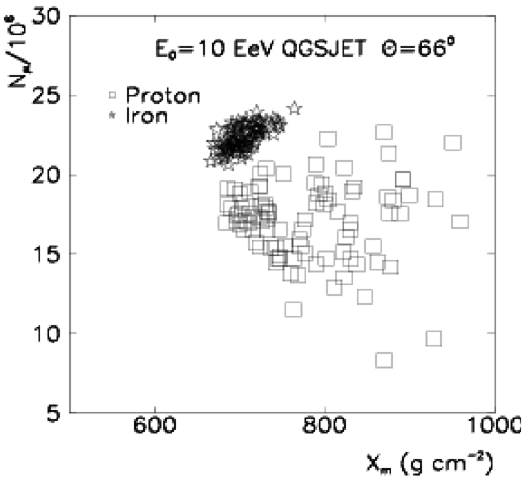

Fig. 1. Correlation between X_m and N_μ obtained with simulations for a zenith angle of 66° and a primary energy of 10^{19} eV.

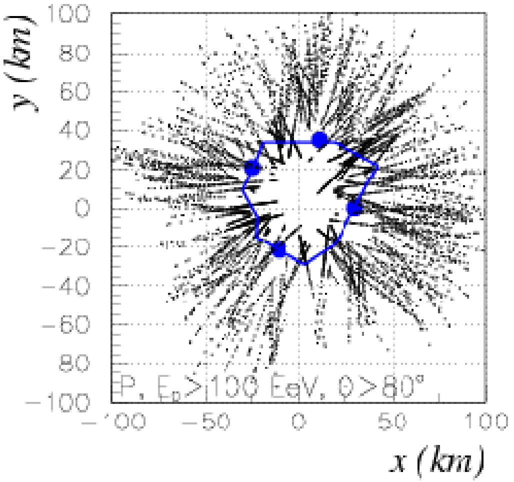

Fig. 2. Simulated ground projected trajectories of hybrid stereo detected EAS for Proton primaries with energies greater than 100 EeV and zenith angles greater than 80°.

arises whether (highly) inclined hadron-initiated showers can be detected by the Auger Fluorescence Telescopes, since for depths exceeding 70° the $N_{e^-e^+}$ size has already diminished by almost three orders of magnitude with respect to the size at shower maximum. In principle, depending on combinations of primary energy, zenith angles and heights above ground, shower detection may become possible. In order to answer this question, we have made a Monte Carlo calculation in which all EAS have been constrained to land (randomly) within the boundaries of the Auger Surface Array. The incoming direction of each primary has been uniformly distributed in azimuth between 0 and 2π, and in zenith angle as $\sin\theta \cos\theta$. Depending on zenith, a vector of length ranging from (90-1,000) km has been built and segmented into 30 m intervals (100 ns intervals along shower axis). At each point the slant depth has been calculated taking into account Earth's curvature. Next, a Gaisser-Hillas function has been used with the functional dependence of shower maximum and shower size at maximum obtained from simulations for proton and iron primaries. Fluorescence yield is calculated from shower size. A mirror trigger condition is met when 4 aligned pixels (out of 5) trigger.

3. Results

We have calculated the Auger hybrid sensitivity based on the detection of 400 iron and 400 proton primaries having energy thresholds of 10 EeV, 50 EeV and 100 EeV (distributed according to a power-law spectrum with differential energy spectral-index of 2.7), and zenith angles above 60°, 70°, and 80°. In Fig. 2 we plot the ground projected trajectories of the part of the track of each shower

Table 1. Montecarlo Auger hybrid Mono and Stereo efficiencies for iron and proton primaries. The numbers in parenthesis are the expected yearly event rate assuming a normalization of the cosmic ray flux at 10 EeV taken from [6].

EeV	Zenith	Fe-Mono	Fe-Stereo	P-Mono	P-Stereo
10	60	0.85 (102)	0.78 (93)	0.84 (100)	0.77 (92)
	70	0.69 (40)	0.54 (31)	0.68 (40)	0.56 (32)
	80	0.08 (1.2)	0.03 (0.45)	0.10 (1.5)	0.04 (0.6)
50	60	0.89 (6.2)	0.85 (6.0)	0.93 (6.5)	0.90 (6.2)
	70	0.81 (2.6)	0.75 (2.4)	0.84 (2.7)	0.76 (2.4)
	80	0.30 (0.24)	0.16 (0.13)	0.34 (0.3)	0.20 (0.16)
100	60	0.94 (1.9)	0.91 (1.82)	0.95 (2)	0.92 (1.84)
	70	0.86 (0.8)	0.81 (0.76)	0.88 (0.82)	0.82 (0.77)
	80	0.43 (0.1)	0.25 (0.05)	0.50 (0.1)	0.30 (0.07)

detected at least by two eyes. The fact that no EAS are detected beyond 82° zenith angle opens the possibility for interpreting any such event as a neutrino-like induced shower [5]. In Fig.2 we can observe the 4 eyes (circles) positioned on the perimeter of the surface array (SA) (each viewing $30^\circ \cdot 30^\circ$ of sky above the SA which is composed by 1600 water Cherenkov tanks -not shown on the graph for clarity- spaced 1.5 km from each other in a triangular pattern). In Table 1 we summarize our results for each combination of primary composition, energy and zenith angle. The hybrid efficiencies are given both for the mono (showers only detected by one eye) and stereo mode (at least two eyes). The numbers in parenthesis are the expected yearly event rate assuming a normalization of the cosmic ray flux at 10 EeV taken from [6].

The aim of this work is to show that hybrid inclined events will be detected by the Auger Observatory. A calculation of the predicted number of events is presented. Further work is in progress to establish the power of these events to estimate mass composition of high energy cosmic rays.

1. Ave, M M., Hinton, J. A., Vázquez, R. A., Watson, A. A., and Zas, E., 2002, Phys. Rev. D65 063007.
2. Sciutto, S.J., 1999, Proc. XXVI Int. Cosmic Ray Conf., vol. 1, p. 411; astro-ph/9911331.
3. Ave, M. et al. 2003, Phys.Rev. D67 043005.
4. Kakimoto, F., Loh, E. C., Nagano, M., Okuno, H., Teshima, M., and Ueno, S., 1996, Nucl. Inst. Meth. Phys. Res. A372, p.244
5. Guerard, C.Kj., 2001, Proc. XXVII Int. Cosmic Ray Conf., vol. 2, HE, pp.760-63.
6. Abu-Zayyad, T. et al., submitted to Astroparticle Physics, astro-ph/0208301