Estimation of the acceptance of the AUGER ground detector to quasi-horizontal showers induced deeply in the atmosphere

Pierre BILLOIR
L.P.N.H.E. Paris VI-VII

1 Introduction

It was pointed out that the Ground Array of the Auger detector could be sensitive to quasi-horizontal showers, induced deeply in the atmosphere by neutrinos (or other weakly interacting objects) that can give rise to an electromagnetic and/or hadronic shower; some rough estimations of the acceptance were given [1]. The aim of this paper is to evaluate this acceptance on a more quantitative basis, through a simplified simulation of the signal seen in the Cerenkov stations, assuming a standard local trigger (not a specific one) and a reasonable global triggering condition.

In order to obtain a parametrization of the development of the shower, we use the output of special MOCCA runs, from a primary proton or photon, at energies 10^{17}, 10^{18} and 10^{19} eV, through an homogeneous atmosphere (with $\rho_{air} = 1\ g.dm^{-3}$, which represents a mean value in the lowest 2 kilometers, where most of the interesting showers expand); the final particles are sampled at different depths from 500 to 1600 $g.cm^{-2}$. As the showers are still active at this last depth (especially the muonic part) we extrapolate the muons beyond this length, accounting for energy loss and possible decay. We consider also conservative assumptions to describe what happens beyond the impact of the core on the ground.

We transform the local densities into a signal amplitude, with a simple evaluation of the energy deposited, and assuming the response of the detector to be linear. Then we define a realistic *local trigger* condition in a tank, and a *global trigger* which is basically the requirement of at least three local triggers (a time alignment condition could be added; it is not yet applied).

Finally, a sample of showers is randomly generated : the primary interaction is uniformly distributed in a large volume surrounding the ground array, and the direction is isotropically distributed between the horizon and an upper limit (typically 15 degrees above the horizon), in a region where the background due to the tails of ordinary showers is assumed to be reduced. From the fraction of observed triggers, we evaluate the acceptance in terms of the *(volume.solid angle)* where a primary interaction can be detected.

For convenience, we distinguish throughout this study the *muonic* and the *electromagnetic (e.m.)* parts of the signal; hopefully they can be separated, to some extent, in a real signal. This could play an important role in the characterization of "deep" interactions (against the penetrating tails of ordinary showers); also, this could help to determine the distance of the primary interaction point, hence a possibility to estimate the energy, which is *a priori* very difficult to reconstruct.

The contribution of other particles is negligible.

2 Parametrizations from MOCCA output

First we point out that most muons have enough energy to go through a tank (up to a full diameter) without stopping, and to give a roughly constant light rate; then the relevant quantity is the *length* of the trajectory in water, and we need to evaluate the numeric density of muons as a function of the position of the tank with respect to the shower, and, to some extent, their angular distribution. On the contrary, most photons and electrons will be absorbed and give a signal roughly proportional to their *energy*; so we want do parametrize the density of e.m. energy density (without distinguishing the electrons/positrons from the photons).

On the other hand, analytic parametrizations of the densities, established to describe vertical showers at ground level, are not useful in this context; the radial and angular profiles depend on the depth.

For a given primary energy, ten showers were simulated at each depth (corresponding to 5, 6, 8, 10, 12, 14, 16 km from the primary interaction). The production of muons is assumed to be negligible afterwards; this is confirmed by propagating back their trajectories : they are found to be originating from the shower axis, with a distribution limited to the first 12 km, even at 10^{19} eV. The muons found at the last depth are extrapolated by steps of 100 m to 18, 20,..., 96 km; random decays are simulated according to the energy, and an energy loss of about 200 MeV per kilometer is applied (more precisely we used an *ad hoc* parametrization $dE/dx = 200 * (0.4 + 0.15 \log_{10} E)$, with E in MeV).

The e.m. activity after 16 km is ignored for the moment, because it cannot be extrapolated in a simple way.

Using weighted sums from MOCCA output, the muon and e.m. density are computed in unequal concentric slices around the core; each subsample is also divided in angular slices with respect to the axis, and in time slices; tables of *density(depth,distance,angle)* and *density(depth,distance,time)* are established. Fig. 1 to 4 show the longitudinal density profiles, and transverse sections at different depths : one can see that the showers are actually truncated by the limited range in depth, then the acceptance may be underestimated. Additional simulations are under way to complete the parametrization.

The geomagnetic field may change the spatial development of the shower: to study this effect, a transverse field of 0.25 Gauss was applied to the extrapolated muons. The effect is not so large as it could be expected, because at large depth the region of highest density is populated by muons of largest energy (the energy is strongly anticorrelated to the angle, hence to the distance from axis at a given depth). Fig.1-4 show that the tail of the shower spreads out, and its efficient volume (where the density is more than 0.4 m^{-2}) is slightly smaller than without field. This effect is ignored later.

To compute the densities at a given point, the tabulated depth closest to the actual one is used; no interpolation is either done between distance or angle bins. Of course, the tables of densities are affected by statistical fluctuations, but it was checked that the effect of the discretization on the estimated acceptance is not dramatic (for example by taking the values from a neighbouring box). There may be an effect on the edges of the sensitive region : the statistical fluctuations on the signals seen by stations far from the core are exaggerated. Different ways of smoothing the parametrization are under study (however, a smoothing procedure may produce biases in a stiff decreasing distribution).

3 The local response of the detector

3.1 Coordinates relative to the shower

Given a point (for example a ground station) we define its coordinates with respect to the shower axis (with the origin at the primary interaction point) as :

- the depth (or longitudinal coordinate) l
- the radius (or transverse coordinate) r, which is the distance to the axis

The angle between the axis and a given direction at this point is written as α.

Assuming symmetry around the axis, these quantities define a box in the parametrizations described above. The impact on the ground is at depth l_{gnd}.

3.2 Muons

For each slice in α, the local muon density is evaluated perpendicularly to the corresponding direction in the meridian plane (defined by the shower axis and the station); it is then multiplied by the projected crossed surface, either on the top of the tank, or on the lateral surface. The numbers of muons (in this α slice) entering

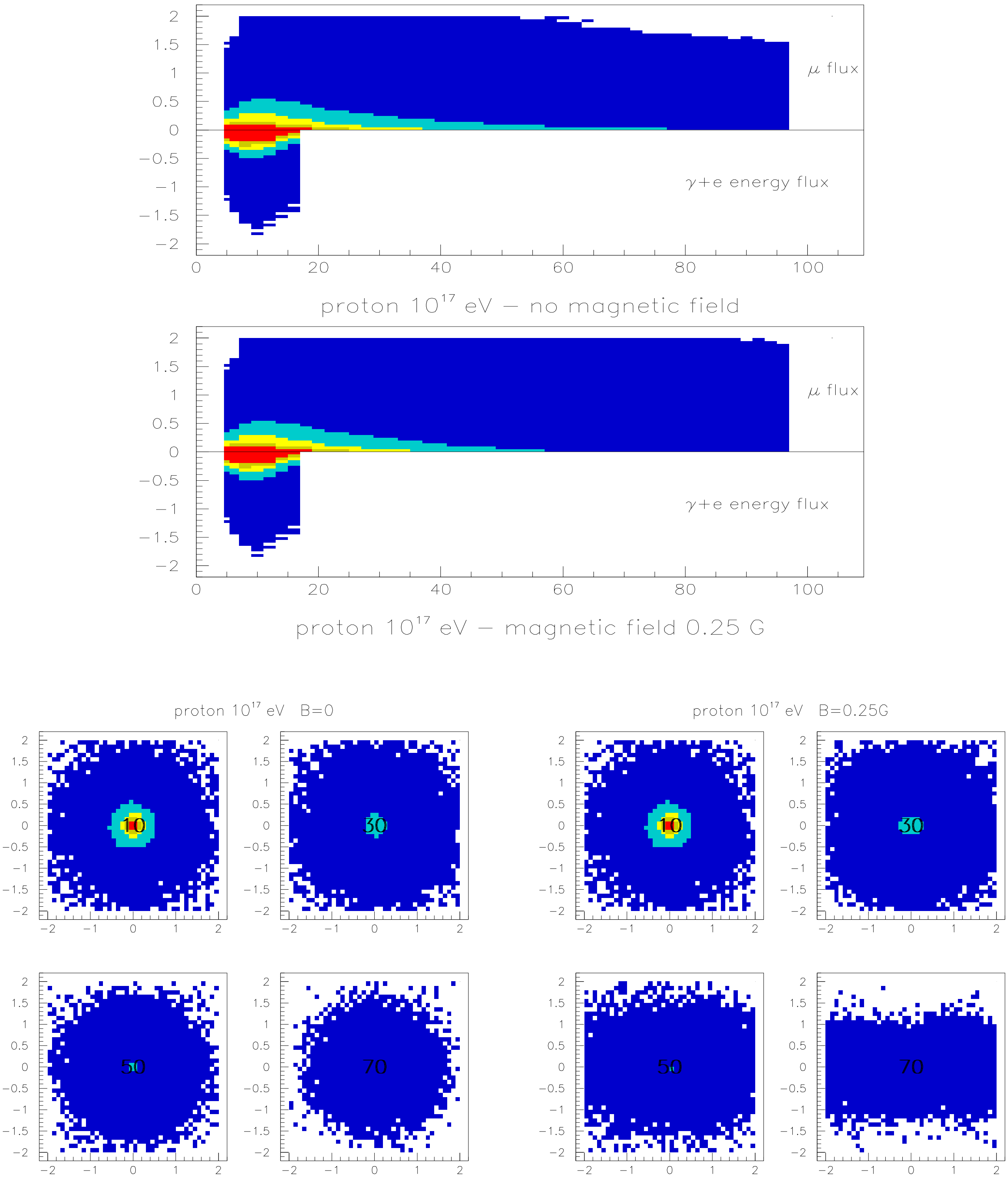

Figure 1: Longitudinal and transverse density profiles (protons at 10^{17} eV)

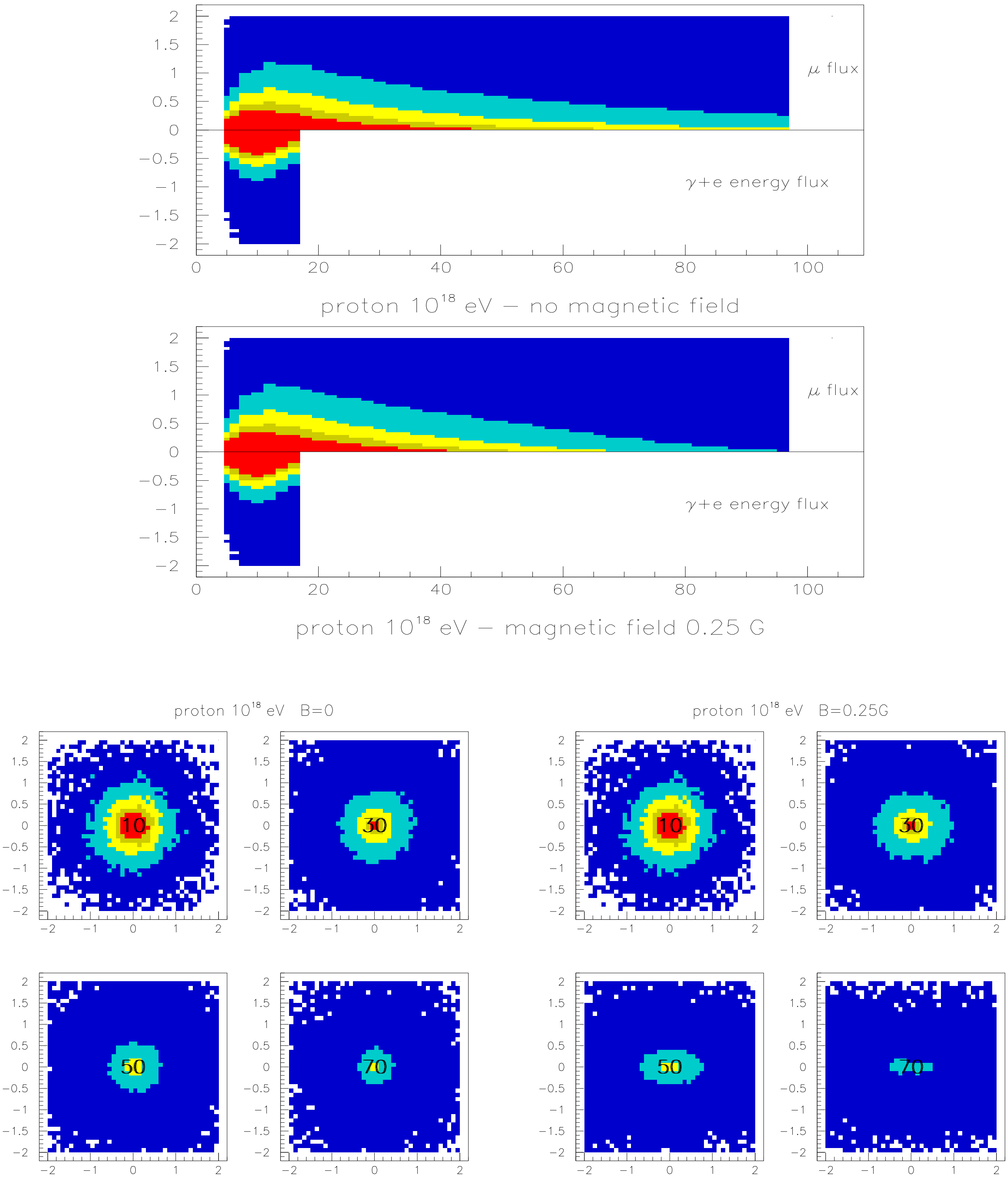

Figure 2: Longitudinal and transverse density profiles (protons at 10^{18} eV)

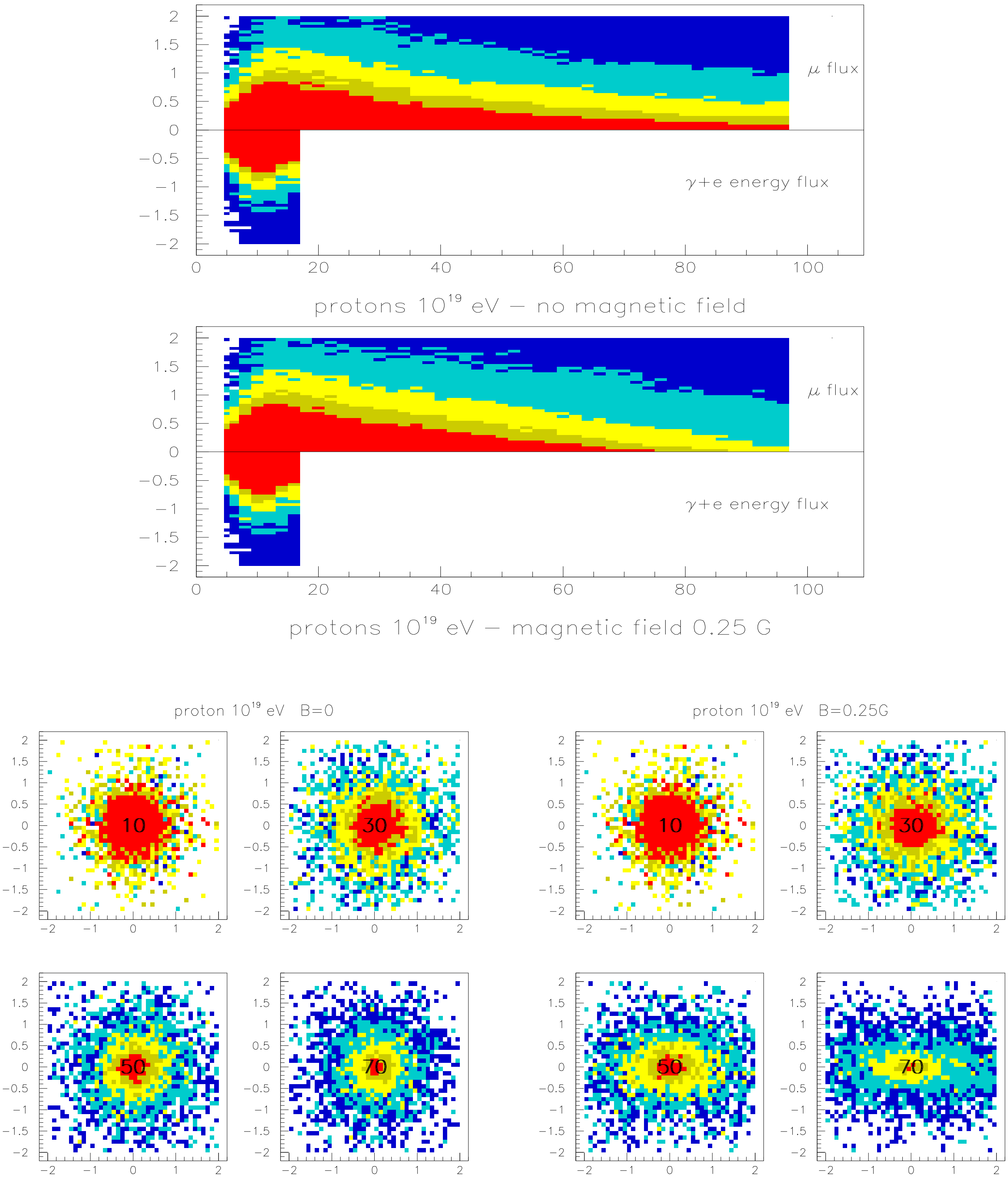

Figure 3: Longitudinal and transverse density profiles (protons at 10^{19} eV)

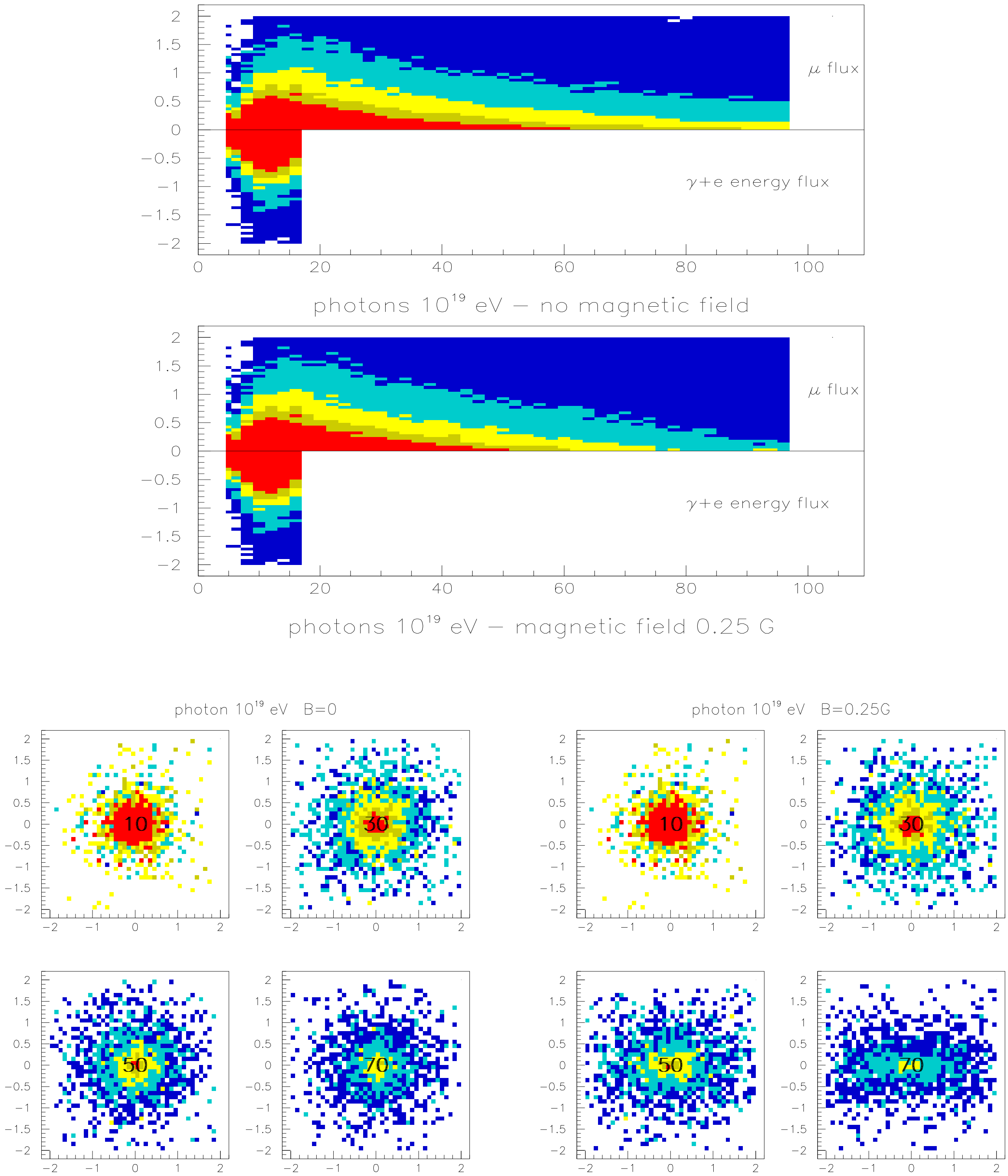

Figure 4: Longitudinal and transverse density profiles (photons at 10^{19} eV)

from the top and from the side is generated according to a Poisson law; then, for each one, an entry point in the tank is determined according to an uniform distribution, and the active length inside the water is evaluated. The "signal" is defined as the sum ΣL of active lengths of all muons. Using a one-by-one input to the detailed simulation of the detector DETSIM [2], we found that the true signal given by he PM's is roughly proportional to the length (within 10 to 20%), whatever the entry point and the direction.

Let us point out that the expectation value of ΣL is the product of the density by the volume, so it is independent of the orientation of the tank with respect to the shower; its Poisson fluctuations is large if the muons are quasi-horizontal, and smaller with an oblique incidence (there are more shorter trajectories inside the tank). The top surface is 10.2 m^2; the projected side surface is 4.3 m^2. The mean length of an horizontal trajectory is $\pi/2.radius$ (2.8 m).

3.3 Photons and electrons

An analogous procedure is followed to compute the *e.m.* signal from the local *e.m.* energy density. As for muons, the top- and the side-entering fluxes are computed separately in each angle slice, because the surfaces are very different, and the angular distribution is relatively wide. The energy is assumed to be completely deposited, so the "signal" is the sum of entering energies ΣE (no fluctuation is simulated). As far as the integral of the signal is concerned, this can be converted into an equivalent length of 5 m/GeV.

3.4 The problem of screening by earth

There is a question that MOCCA does not answer : what happens in the development of the shower when the core hits the ground ? From physical arguments and from the observed alignment of their trajectories, we can reasonably assume that the muons come directly from the core ; on the other hand, a muon produced in earth can probably never reach a ground station. This "sharp screen" is easily simulated at $l > l_{gnd}$ by restricting the angles to the region where the core is visible, that is $\tan(\alpha) < r/(l - l_{gnd})$. This restriction has no effect if l_{gnd} is larger than the muon production region, typically 10 km.

The behaviour of the *e.m.* component is less clear. In the pessimistic option, we assume that it disappears completely at $l > l_{gnd}$. In the optimistic option, we apply the same angular cut as for muons; this is supported the following observation : although the *numeric* distribution of photons/electrons is dispersed, the *energy* density is concentrated in the meridian plane (the most energetic ones keep more or less their direction from the core). Then it is not unrealistic to suppose that the *e.m.* energy mainly propagates in straight line, as muons do. Both the optimistic and pessimistic options are used to evaluate the acceptance.

4 Triggering conditions

4.1 Local trigger

The local trigger condition will be optimized to fulfill the main goal of Auger, that is to detect vertical showers and reject background. It is not yet exactly defined, but a conservative assumption is that the integral of the signal should correspond at least to 4 vertical muons; this translates into : $\Sigma L(m)+5\Sigma E(GeV) > 5$ (see above for the conversion factor).

For example, if the incidence is almost horizontal, this is obtained with a pure *e.m.* density of 200 $MeV.m^{-2}$, or a pure muon density of 0.4 m^{-2} (in this case there are large Poisson fluctuations). The corresponding contours are given in Fig.1-4; of course in the overlapping muon-*e.m.* region, the signals sum up and the zone of probable trigger is wider.

4.2 Global trigger

Here a specific condition is to be defined for horizontal showers. In this preliminary study we use a very simple definition : at least 3 stations are locally triggered. If needed (for example to reduce the number of configurations to be examined), one can request, without loosing more than a few percent efficiency, that at least 2 of the triggered stations are adjacent.

The background rejection could be improved (at least off-line) by using the time alignment of the signals if different stations. We can assume that the beginning time will be determined with an accuracy of 100 ns or better; on the other hand the front of the shower hits the stations at times linearly related to the longitudinal coordinate l, within 200 ns (or even better at large values of l). This is small compared to the travel time between two stations (5 μs along the axis), and the constraint is rather strong.

5 Results of the simulation and estimation of acceptance

Primary interactions were generated uniformly on a large surface (160x160 km^2) around the array, with an altitude between 0 and 10 km; the direction is isotropic within $0 < \cos(\theta) < 0.25$. The distributions given in Fig.5 show that, at 10^{17} and 10^{18} eV, this region is large enough to avoid edge effects; actually the acceptance is

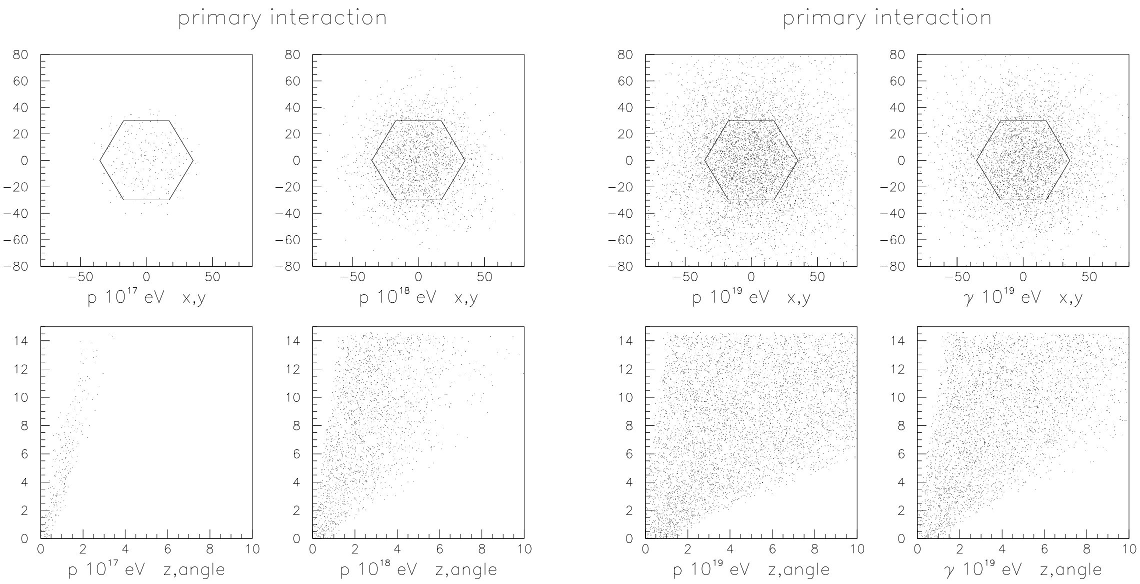

Figure 5: Distributions of primary interactions and angles of detected showers

limited by the range in θ. At 10^{19} eV, the acceptance is probably underevaluated; however the assumption of homogeneous atmosphere and flat ground are questionable if we go farther than 80 km in distance and 10 km in altitude. A dedicated simulation would be needed.

Let us point out that information will also be available from stations which do not trigger. Defining the "minimal" information to be $\Sigma L > 1$ m (or the equivalent *e.m.* deposition), we give in Fig. 7 the distributions of N_{trig} (number of locally triggering stations) and N_{info} (number of stations giving information) for muons and *e.m.*.

Some showers at 10^{18} eV fulfilling the global trigger conditions are shown on Fig. 6, with the response of ground stations. The shape is of course stretched along the shower axis, and the stations contributing to the trigger are often aligned; however, if we take into account the stations above a realistic threshold (typically 200 MeV deposited), the lateral extension of the active region is sufficient to reconstruct the incident direction from the arrival times, and also from the shape of the "spot", with an accuracy of a few degrees (*preliminary, in progress*). The amplitude of the signals could help to constrain to position of the axis, but there is no obvious way to do it without knowing *a priori* the energy and the depth, which are themselves difficult to evaluate. A combined analysis would be needed to fit all parameters together (provided the spot is large enough).

Finally the acceptances are, for proton induced showers (in $km^3.sr$ of equivalent water):

- at 10^{17} eV : 2.3 (1.6)

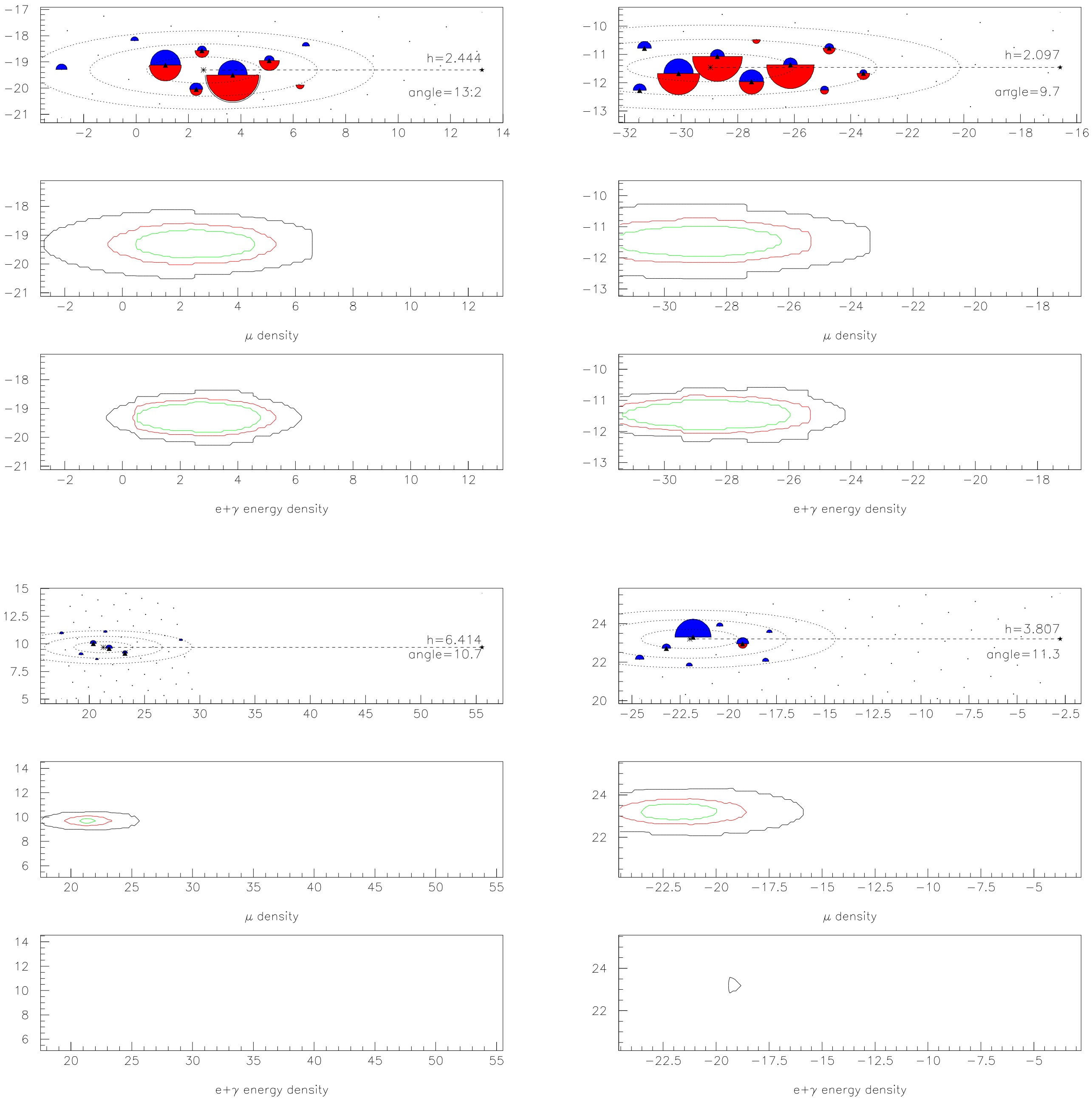

Figure 6: Examples of ground array response to proton showers at 10^{18} GeV

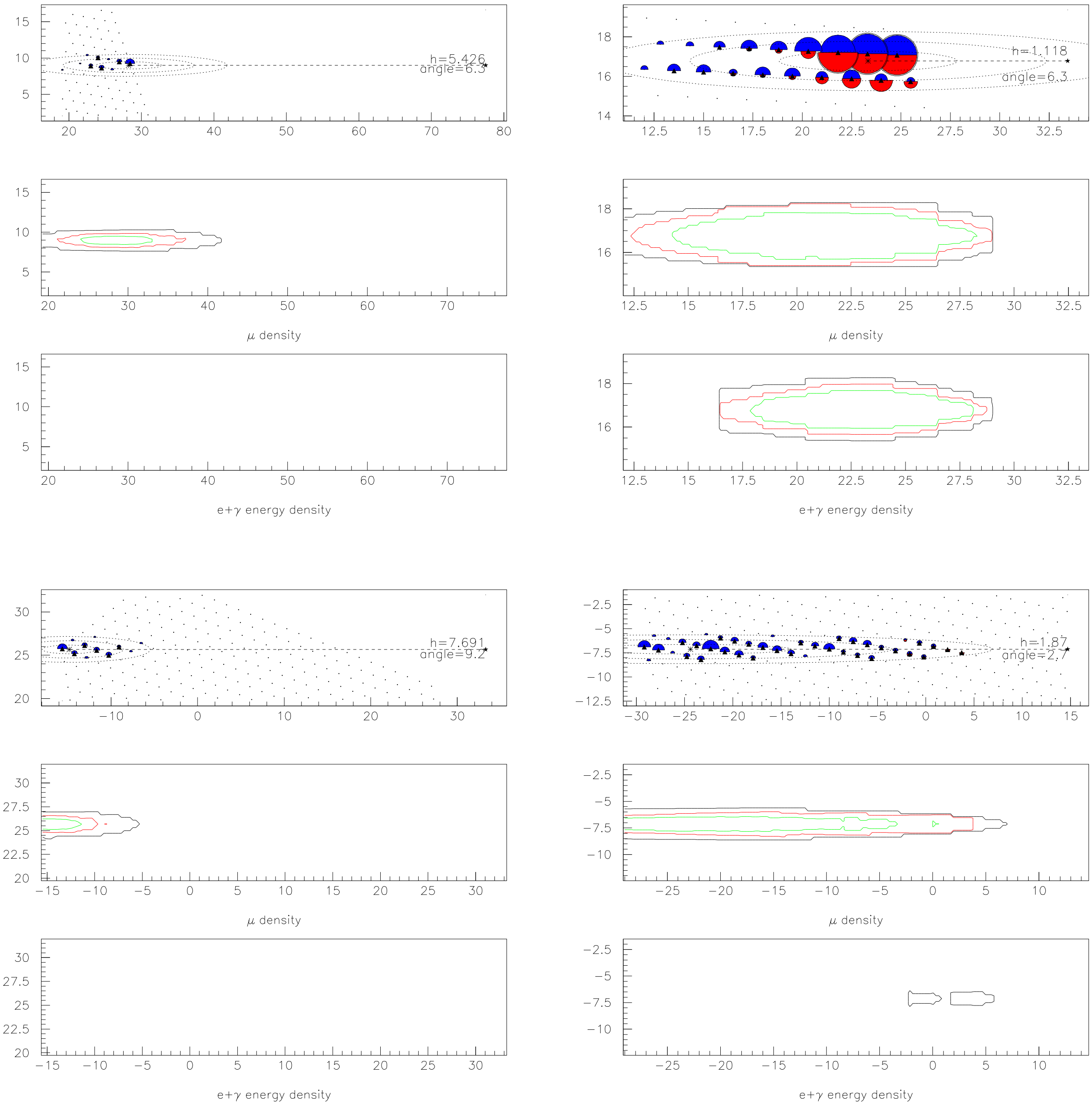

Figure 7: Examples of ground array response to proton showers at $10^{19}\ GeV$

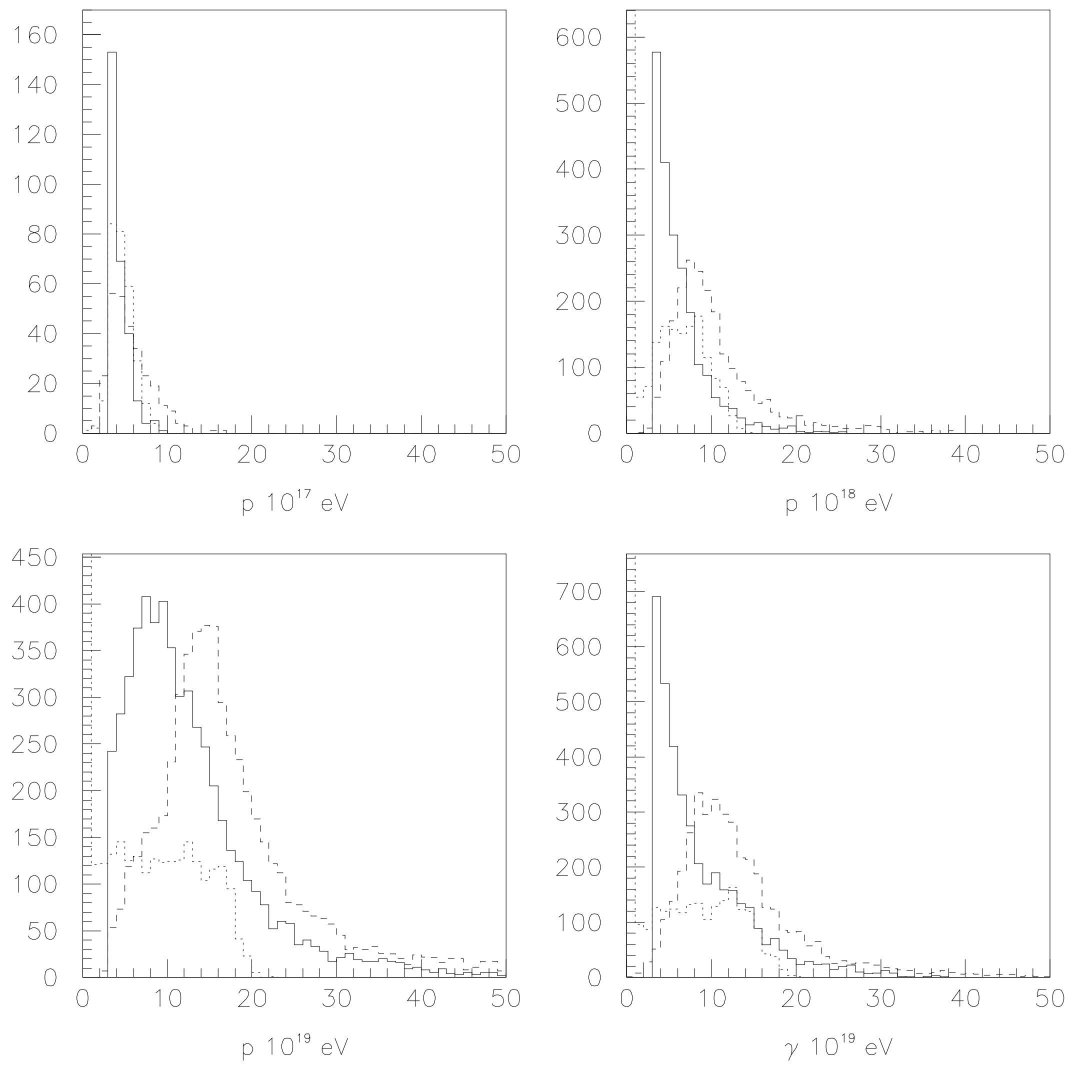

Figure 8: Number of ground stations activated per shower

- at 10^{18} eV : 17.2 (16.8)
- at 10^{19} eV : 43.2 (43.2)

For photons at 10^{19} eV : 31.4 (31.4)

The values in parentheses are found in the "pessimistic" hypothesis for *e.m.* screening by earth (see above); they are not different at high energy because the muons suffice to trigger in the region where the *e.m.* component is neglected.

Requiring at least 4 triggered stations would reduce this values by about 60% (at 10^{17} eV), 30% (at 10^{18} eV), 10%(at 10^{19} eV). Requiring at least one station with a detectable *e.m.* signal would reduce them by 2% (at 10^{17} eV), 30% (at 10^{18} eV), 60% (at 10^{19} eV).

The neutrino induced showers are expected to look like a proton shower with a fraction of the neutrino energy (neutral current or charged current giving a non-decaying heavy lepton), or something between the proton and the photon shower with the full energy of the neutrino (charged current giving an electron)

6 Concluding remarks and possible improvements

The Auger detector array is sensitive to horizontal showers above 10^{17} eV of deposited energy, with an acceptance larger than 1 $km^3.sr$ of water, and increasing rapidly with energy.

The muon content seems to play an important role in the longitudinal extension of the sensitive region of the shower. However an *e.m.* component, which is a crucial criterion to prove that the primary interaction is actually deep, will be present in most triggers (at least at "low" energy).

The topography of the ground around the array could be used to give a clear signature of a deep interaction in certain directions: the mountains are a perfect absorber of anything coming from the opposite side; moreover neutrinos interacting in the rock just before going out could give a detectable shower.

The information in ground stations will probably allow to reconstruct the direction of the shower axis with an accuracy of a few degrees or better, using the geometrical pattern and the times. The evaluation of the energy is more delicate.

The parametrization is still limited by the range in depth. Moreover the ground screening effects are not properly simulated. AIRES is now available to give a realistic description of quasi-horizontal showers (*work in progress*).
The simplified simulation program is used also to build an input to DETSIM in order to account for fluctuations in the response of the detector.

The detection of such showers by the fly's eye would be very helpful. Unfortunately the number of events seen by both detectors is probably too small to allow an efficient cross-check.

References

1. G. Parente, E. Zas : Neutrino induced events in the Pierre Auger detector (Proceedings of the 7th Int. Workshop on Neutrino Telescopes - Venice March 1996.)
2. C. Pryke : DETSIM simulation program

Figure captions

1. Profile of showers simulated by MOCCA in an homogeneous atmosphere ($1\ g.dm^{-3}$). The first page give the longitudinal development (depth in km, distance to core in m), without magnetic field (top), or with a transverse component of 0.5 G (bottom). The upper part represents the muon density (beyond 16 km, it is an extrapolation), with contour levels 2 , 1 , 0.4 , 0.1 m^{-2}; the lower part is the photon+electron energy density with the same levels in $GeV.m^{-2}$. Then there are transverse sections at different depths from 10 to 70 km. Fig. 1 represents showers induced by protons at $10^{17}\ eV$.
2. The same with protons at $10^{18}\ eV$.
3. The same with protons at $10^{19}\ eV$.
4. The same with photons at $10^{19}\ eV$.
5. Distributions of primary interactions and angles of detected showers: protons at 10^{17}, 10^{18}, $10^{19}\ eV$ and photons at $10^{19}\ eV$.
6. Configurations of ground detector signals given by showers at $10^{18}\ eV$.
   - top : general view : a triangle is a triggering station; the blue and red surfaces are proportional to the muonic and $e.m.$ signal (saturation is indicated by a double circle); the shower axis starts at the star (height and angle in degrees from horizon are given) and hits the ground at the asterisk. The dashed ellipses are at 500, 1000 and 1500 meters from the axis.
   - middle : countours of parametrized muon density (at 0.1, 0.4 and 1 m^{-2}) at the level of the ground. - bottom : contours of parametrized $e.m.$ energy density (at 0.1, 0.4 and 1 $GeV.m^{-2}$)
7. The same at $10^{19}\ eV$.
8. Global triggers: distribution of the number of stations giving a local trigger (solid line), muonic information (dashed), $e.m.$ information (dotted).