GAP-98-034, Auger project technical note. Asymmetry of Air Showers at Ground Level

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Abstract

It is frequently assumed that the signals observed when an extensive air shower strikes a ground array depend only on perpendicular distance from the shower axis (core distance). For inclined events this might not be the case due to continuing longitudinal development of the cascade. Even for near vertical showers axial symmetry could be disrupted by the action of the geomagnetic field. In this paper it is shown through shower simulations that the former effect is dominant (for $E > 10^{19}$ eV and $\theta < 60$ deg). The asymmetry is found to be significant in the context of widely spaced arrays: a factor of ~ 3 at 45 deg zenith angle and core distance of ~ 1.5 km, when observing with water Čerenkov detectors.

1 Introduction

In analysis of experimental data, and shower simulation output, it is usually assumed that the footprint of an extensive air shower in the plane of the ground has elliptical symmetry centered on the shower axis, and that a simple transformation projecting the observations into a plane perpendicular to the shower axis restores circular symmetry. Hence only the radial distance (impact parameter) of the particles or detectors need be considered.

In fact for non-vertical showers this is clearly not the case as the cascade continues to develop as the shower disk passes into the ground; the particles which strike the ground first represent an earlier stage of development than those which arrive later. Even for near vertical showers, asymmetry is possible due to the effects of the geomagnetic field.

The assumption that detector signals depend only on perpendicular distance from the shower axis is the corner stone of the ground array technique. At small zenith angles, and modest core distances it is a good approximation. However, due to the extremely low flux of cosmic rays at the highest energies there is a strong imperative to construct arrays with very large inter-detector spacings (~km), and to observe out to large zenith angles (up to 60 deg). It is thus important to consider whether the assumption still holds under those conditions.

In this paper the magnitude of the asymmetry is investigated via shower simulation, using some runs made specifically for this study, and also a library of general purpose events with varying energies and zenith angles.

1.1 Geometrical Asymmetry

Figure 1 illustrates three cases. The intersection of a cylinder and a plane is a circle if the two are perpendicular, and an ellipse if they are inclined. In the case of an inclined cone the intersection is also an ellipse, but it is not centered on the conical axis (it is eccentric).

Ground array data is normally analyzed on the assumption of cylindrical symmetry (the first 2 cases of figure 1). In fact an air shower cascade disk first grows and then contracts as it passes down through the atmosphere. Ground level is normally beyond the point of maximum development. The third case of figure 1 may be thought of as representing a particle isodensity contour traced out in 3-dimensional space over time (higher density within, lower outside).

In this conical scenario a series of 2-dimensional isodensity contours in the ground plane are increasingly eccentric ellipses. When projected into a plane perpendicular to the conical axis the eccentricity is reduced, but not eliminated; figure 2 illustrates this[1].

[1] If the conical axis is at a zenith angle θ, the cone half angle is α and the semi-minor axis of an ellipse in the ground plane is r, then the distances from the conical axis to the edge of the ellipse along the major axis are $r_1 = r\sin(90-\alpha)/\sin(90+\alpha-\theta)$ and $r_2 = r\sin(90+\alpha)/\sin(90-\alpha-\theta)$. The semi-major axis is then $(r_1+r_2)/2$ and the

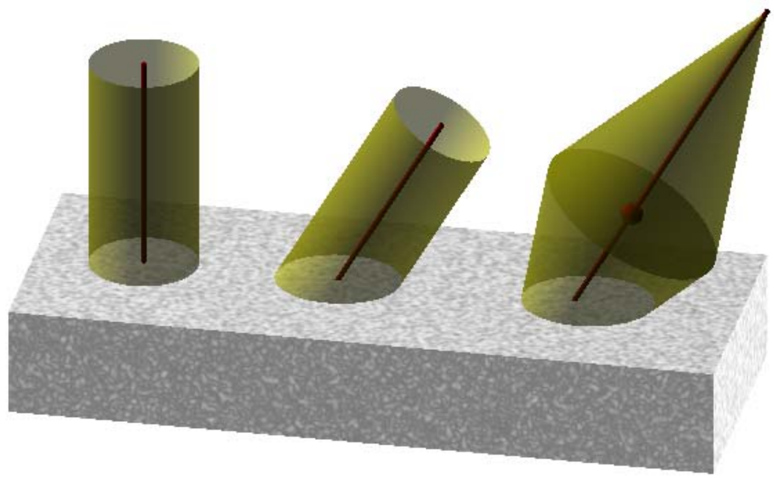

Figure 1: The intersection of a vertical cylinder, an inclined cylinder, and an inclined (inverted) cone with the ground plane.

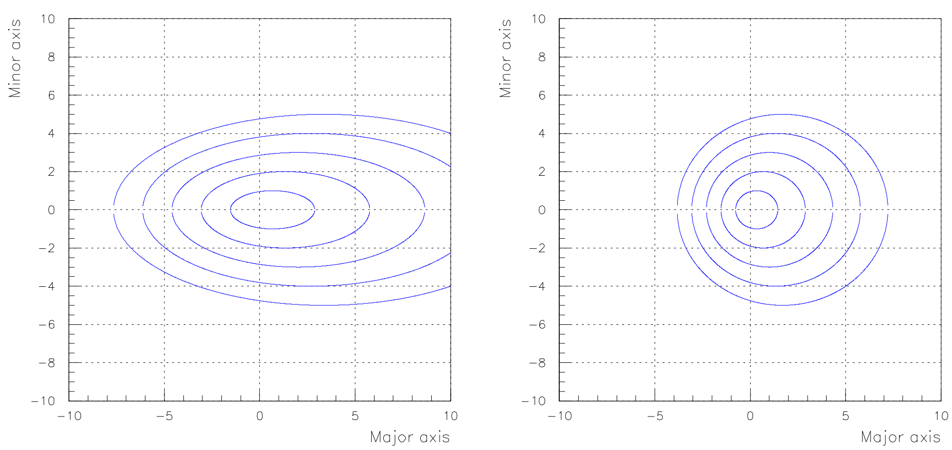

Figure 2: At left elliptical contours produced by the intersection of a series of cones inclined at 60 deg to the vertical with the ground plane (cone half angle 10 deg). At right these contours are projected into a plane perpendicular to the conical axis; they remain elliptical and eccentric.

In reality the structure of an air shower will be more complex. However, as we will see later, an inverted cone seems to be a reasonable first approximation.

1.2 Geomagnetic Asymmetry

When an air shower arrives at an angle to the earth's magnetic field the charged particles in the cascade can be deflected. Muons travel large distances through the atmosphere without interacting, and can acquire significant deflections from the path they would have traveled in the absence of a magnetic field. Figure 3 illustrates the deflections for a shower arriving from the direction of magnetic north at a zenith angle of 60 deg. The dip angle is also set to 60 deg — the value in the southwestern US [1]. Hence the shower arrives perpendicularly to the geomagnetic field, which, for the purposes of illustration, is set to five times stronger than reality (250 μT rather than 50 μT).

2 Studying Asymmetry with Special Events at Large Zenith Angle

MOCCA [2], and other air shower simulation programs, follow the cascade particles explicitly in 4-dimensions and deliver a ground particle output list. However, due to the very low thinning level[2], and hence large amount of computing power required to investigate asymmetry effects, this has not often been done in the past.

For the purposes of this study we define the ground and shower reference frames. The ground frame is as follows: x, y and z axes are magnetic north, west and up respectively. The shower frame is obtained by a rotation about the z axis, through the azimuthal angle of the direction in which the shower is going, followed by a rotation about the y axis, through the zenith angle

offset of the elliptical center from the conical axis $(r_2 - r_1)/2$. When projected into a plane perpendicular to the conical axis each of these quantities simply scale as $\cos(\theta)$; $\cos(\theta)(r_1 + r_2)/2 > r$ so the contours remain elliptical and eccentric.

[2]Thinning is a technique used to accelerate the simulation of high energy cascades. All particles are tracked down to an energy defined as a fraction of the primary energy — below this threshold only a sub-set of particles are tracked. The 10^{-8} thinned events generated for this paper took ~ 4 days each on 180 MHz R10000 CPUs.

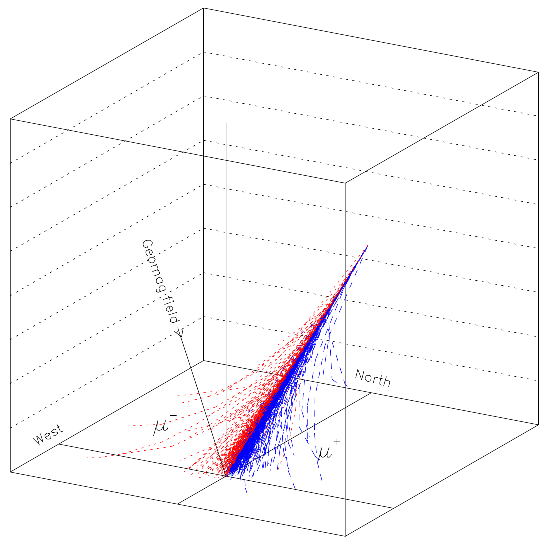

Figure 3: Geomagnetic deflections in a shower arriving from the direction of magnetic north at a zenith angle of 60 deg. The field is five times stronger than actual. Positive muon tracks are dashed, and negative dotted.

(θ). Thus the z' axis lies along the shower core, and the intersection of the shower disk and the ground plane is a line parallel to the y' axis, moving in the positive x' direction as time progresses.

The z' component of the particle ground positions can be used to correct the arrival times, and so investigate the time structure of the shower front — however, this line of inquiry is not pursued here. The $x'y'$ components we refer to as being the particle positions in the "shower plane" or "in a plane perpendicular to the shower axis". The "perpendicular distance from the shower axis" or "core distance" is simply $\sqrt{x'^2 + y'^2}$.

Figure 4 shows the density of muons in the ground and shower planes for a single 10^{19} eV MOCCA-Sibyll [3] proton shower thinned at 10^{-8}. The primary arrives at 60 deg to the zenith from 30 deg east of south (lower left). (First interaction at 32 g cm^{-2}.) This zenith angle is chosen since it has been stated to be the maximum at which the Auger ground arrays will be able to confidently reconstruct conventional air shower events. Approximately 1.6×10^6 (unweighted) muons appear in the output list. The upper two plots are in rectangular coordinates (200 m $\times$ 200 m bins), and the lower two are in polar coordinates (15 deg $\times$ 200 m bins). The left two plots are in the ground plane, and the right two in the shower plane. (Looking vertically down from above the ground, and looking along the shower axis respectively). The intersection of the shower disk and the ground plane is a line perpendicular to the arrow marked “arrival”, moving along the direction of that arrow as time progresses. The quadrants are indicated which are referred to as “left”, “right”, “late” and “early”.

Note the expected gross symmetry; elliptical in the ground plane, and circular in the shower plane. Also note the late-to-early asymmetry caused by muons ranging out (and decaying in flight) as the shower passes across the ground. Recall that we are looking for patterns analogous to figure 2.

Figure 5 shows the ratios of the left-to-right, and late-to-early quadrants versus core distance for gammas, electrons and muons. For this simulation the geomagnetic field was switched off. Hence we expect perfect left-to-right symmetry; the deviations from that are due to the limitations of even 10^{-8} thinning. For a 60 deg zenith angle shower the electromagnetic particles are already severely attenuated, and decaying fast; they exhibit a strong late-to-early effect (factor of ~ 10). The muons with their higher energies, and longer paths, attenuate less while crossing the shower footprint (factor of ~ 3).

To further quantify geometrical asymmetry it is necessary to consider a specific type of ground detector, since different detectors may give different results. The Auger Project has elected to use Water Čerenkov detectors 1.2 m deep; these produce a much larger signal when penetrated by a (GeV) muon than by an (MeV) electromagnetic particle. The relative response as predicted by AGAsim [4], and used in this study, is shown in figure 6 — the exact shape of these curves is not critical. Additionally since the dependence of the shape of these curves on zenith angle is found to be very small for a 10 m^2 cylindrical detector it is ignored. (The signal from muons below the Čerenkov threshold comes from their decay electrons.)

A 10^{19} eV MOCCA-Sibyll proton shower thinned at 10^{-8} was simulated arriving from magnetic north at a zenith angle of 60 deg. (First interaction at 13 g cm^{-2}.) The geomagnetic field was switched off. For each particle arriving at ground level the relative response in units of vertical equivalent muons (VEM) was taken from the curves in figure 6. A polar histogram (r, ϕ) in the shower plane was then filled, with bins 15 deg wide, and 0.5 units long in the dimension $\log_{10}(r)$. We expect the late-to-early asymmetry to be a first harmonic effect; a suppression at 0 deg polar angle, and an

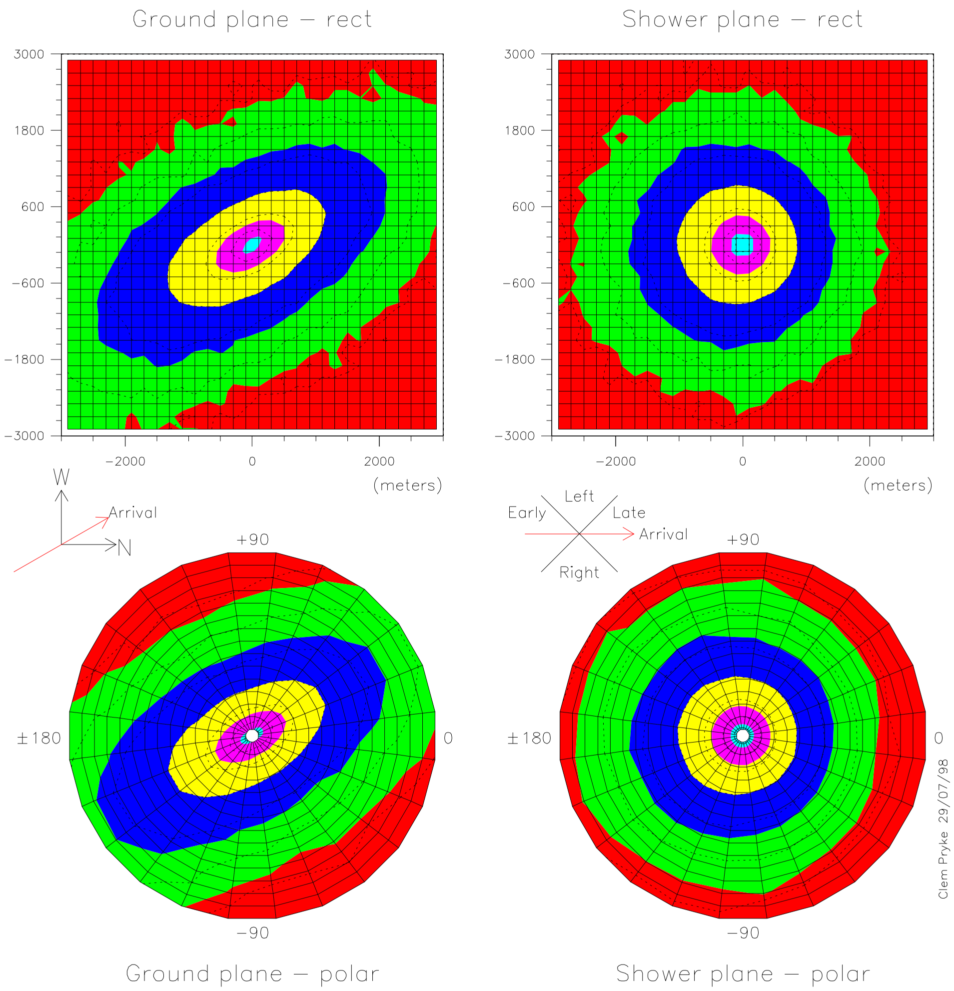

Figure 4: Muon density for a 60 deg zenith angle shower plotted in the ground and shower planes, and in rectangular and polar coordinates. The color scale is logarithmic, and the same in each case.

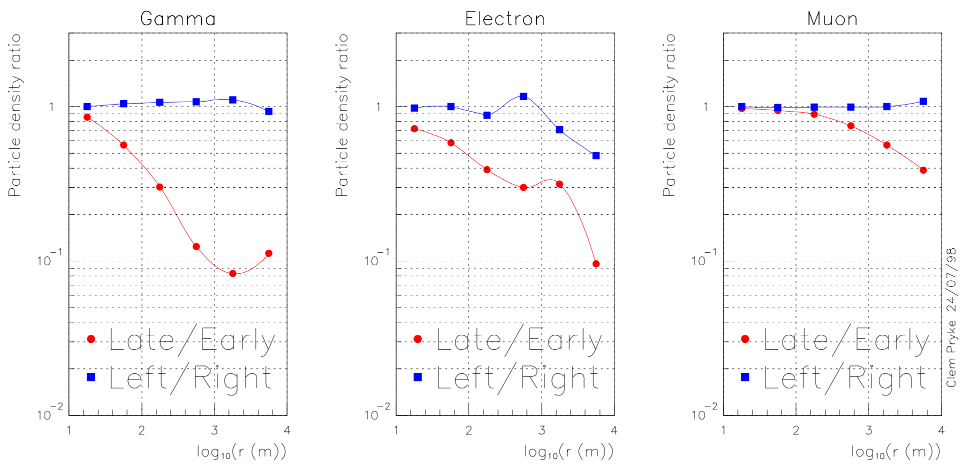

Figure 5: Left-to-right and late-to-early ratios versus core distance for gammas, electrons and muons in a 60 deg zenith angle shower.

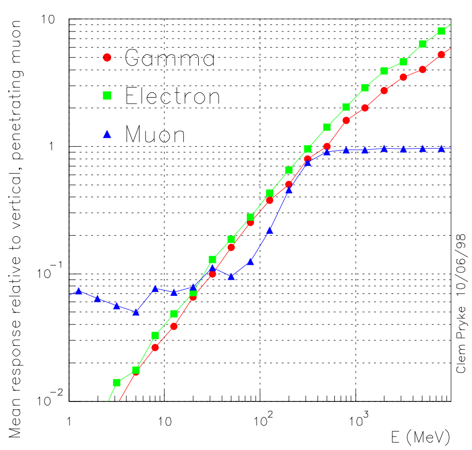

Figure 6: Relative response of a 1.2 m deep water Čerenkov detector.

enhancement at ±180 deg. Figure 7 shows that this is the case[3]. Also note that the magnitude of the effect increases with core distance.

For a shower arriving at a large zenith angle, and at a large angle to the geomagnetic field, muon deflections can be significant. Figure 8 illustrates this using the same event as figure 7, but with geomagnetic deflections switched on. The field is set for a site in the southwestern US; dip angle 60 deg, strength 50 μT. A shower arriving from magnetic north at a zenith angle of 60 deg moves perpendicularly to the geomagnetic field, and the deflections will be the maximum possible for any $\theta \leq 60$ deg.

Most ground array detectors are not sensitive to the charge of muons — certainly water Čerenkov detectors are not. Additionally the charge ratio of shower muons is not very far from unity (there is a small positive excess). Hence although the existence of the geomagnetic field may distort the muon charge ratio in the "left" and "right" regions, the overall muon density is not greatly altered.

Figure 9 is analogous to figure 7, but with geomagnetic deflections switched on (same run as figure 8). For a shower coming directly from magnetic north we expect enhancement peaks at ±90 deg. Comparing the two plots carefully the geomagnetic effect can be seen, but it is clearly much smaller than the geometric. This might not be true at other geographic locations, or at larger zenith angles, or in fact for another event with the same parameters; however it appears to be a valid assumption for the events investigated in this paper (see appendix A). Of course it would also not be true if the Earth's magnetic field were stronger. Purely for illustration figure 10 shows the same event again, but with the field increased by a factor of five — now the situation is reversed and the geomagnetic effect dominates over the geometric.

3 Studying Asymmetry in a MOCCA Shower Library

A library of 1000 MOCCA-Sibyll events thinned at 10^{-7} was generated to act as input for Auger detector simulations [5]. The library includes events from $10^{19.1}$ to $10^{20.7}$ eV and zenith angles from 0 to 63 deg (with the $\sin\theta\cos\theta$ distribution appropriate for a ground array). The primaries are an equal

[3]The function fitted is $\rho(\phi) = a - b\cos(\phi)$, where a is the mean value and b is the amplitude of the sinusoidal variation. The late/early ratio is thus $(a-b)/(a+b)$.

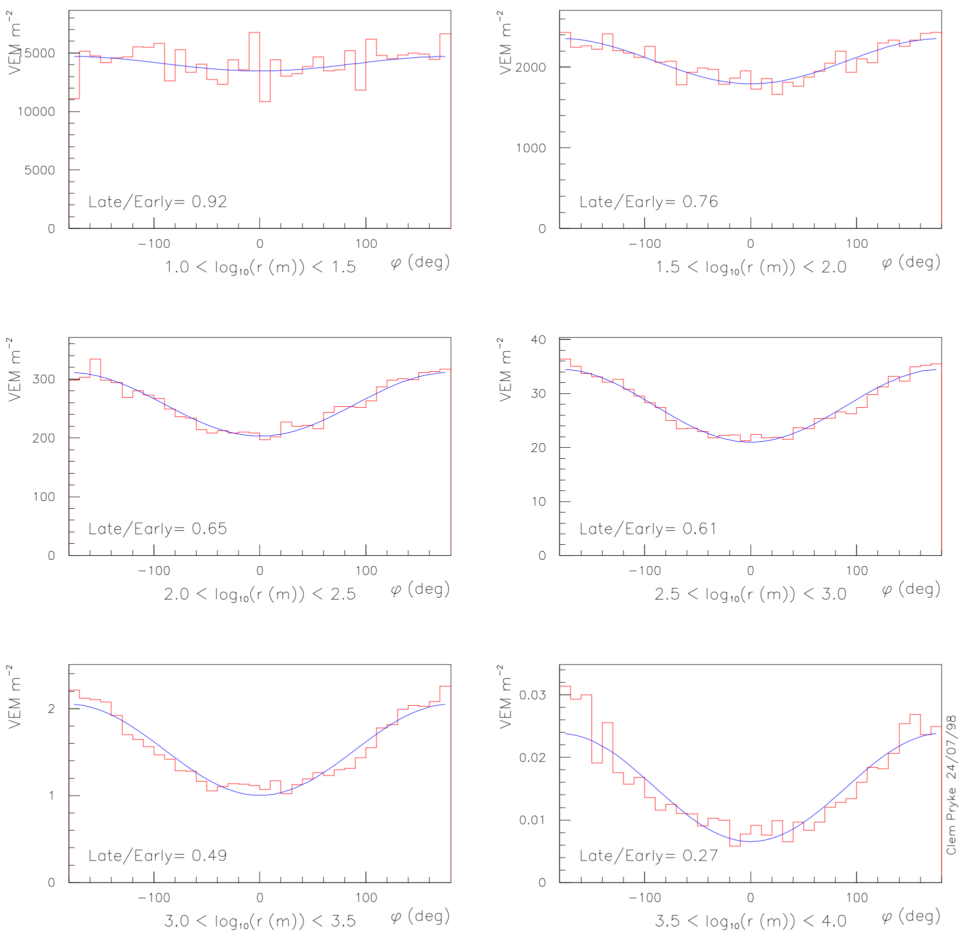

Figure 7: Water Čerenkov detector signal versus polar angle ϕ in the shower plane. Plots are shown for six logarithmic core distance annuli. A first harmonic fit is shown in each case with the minimum to maximum ratio indicated. The geomagnetic field is switched off.

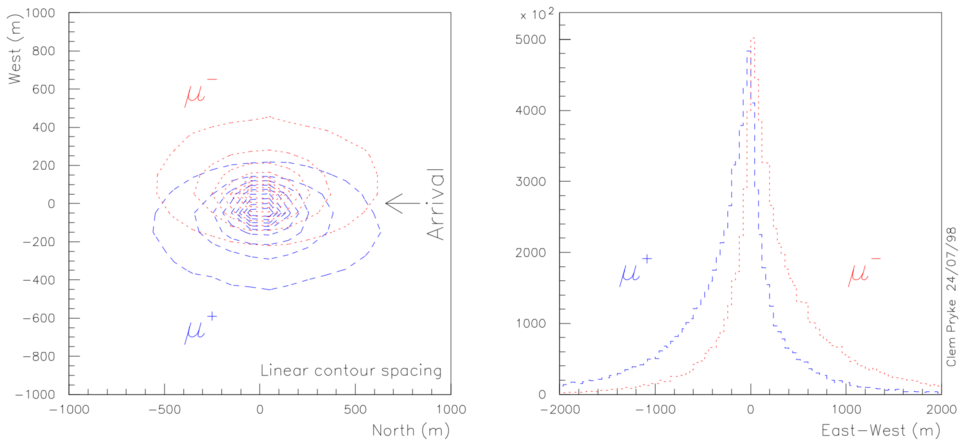

Figure 8: At left equal density contours are plotted for positive and negative muons in the ground plane. The contour spacing is linear. At right histograms of east-west muon position are shown. Positive muons are dashed, and negative dotted.

mix of protons and iron nuclei, and the primary energies are chosen from an artificially flat $dN/dE \propto E^{-1}$ spectrum. As above, the geomagnetic field was set to that of the southwestern US (dip angle 60 deg, strength 50 μT). The ground particle output list from each of these events was processed to produce polar histograms of particle density in the shower plane, and also similar histograms with the response of a water Čerenkov detector folded in, in the same way as before. A first harmonic function was then fit in the core distance annulus $1 < r < 3$ km. It is in this range that a $\sim$ km spaced ground array like Auger makes the bulk of its observations.

Figure 11 shows the result for a single shower — the first in the library, with a zenith angle of 24 deg. Plots are shown for numerical density of gammas, electrons and muons, and also their contributions to the water Čerenkov signal; the total signal is also shown. It is clear that the statistics of events thinned at 10^{-7} are barely adequate. In this core distance range the contribution of gammas and muons is approximately equal (that of electrons is much smaller). Hence the asymmetry curve for total signal is mid-way between between those two cases. Note that the muons show a weaker effect than the electromagnetic particles, as expected due to their higher energies,

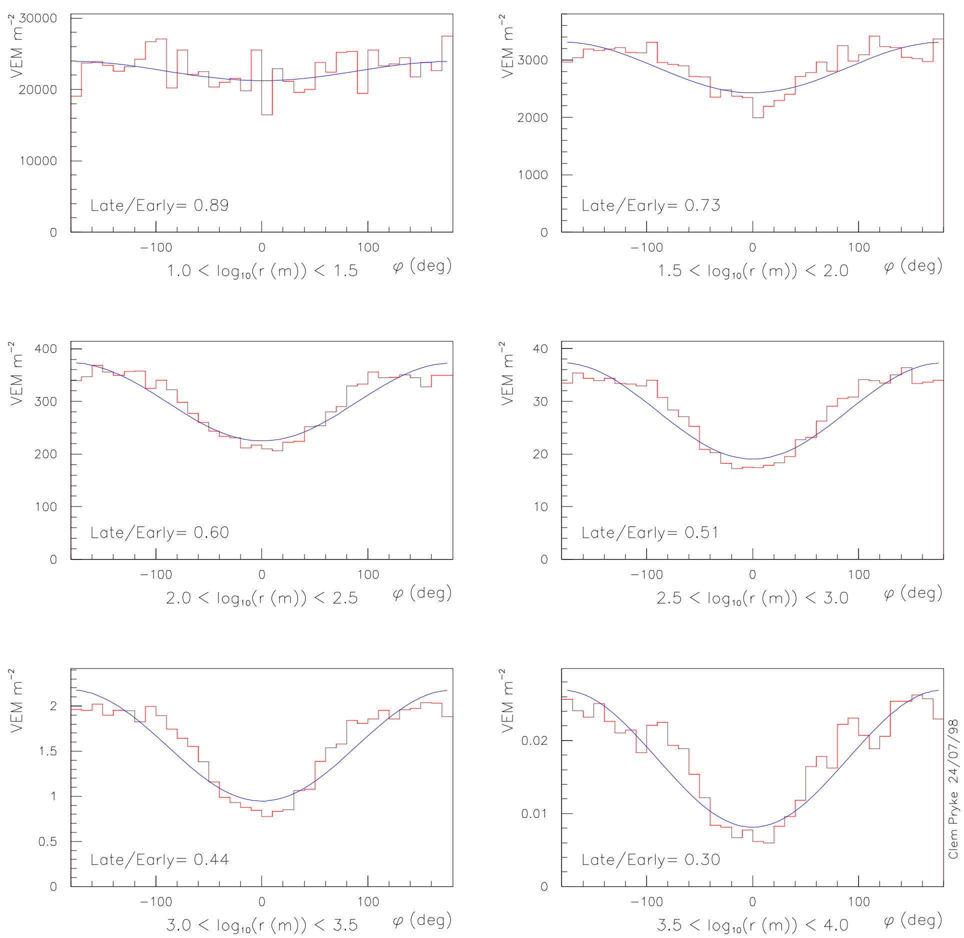

Figure 9: This plot is analogous to figure 7, but with the geomagnetic field switched on.

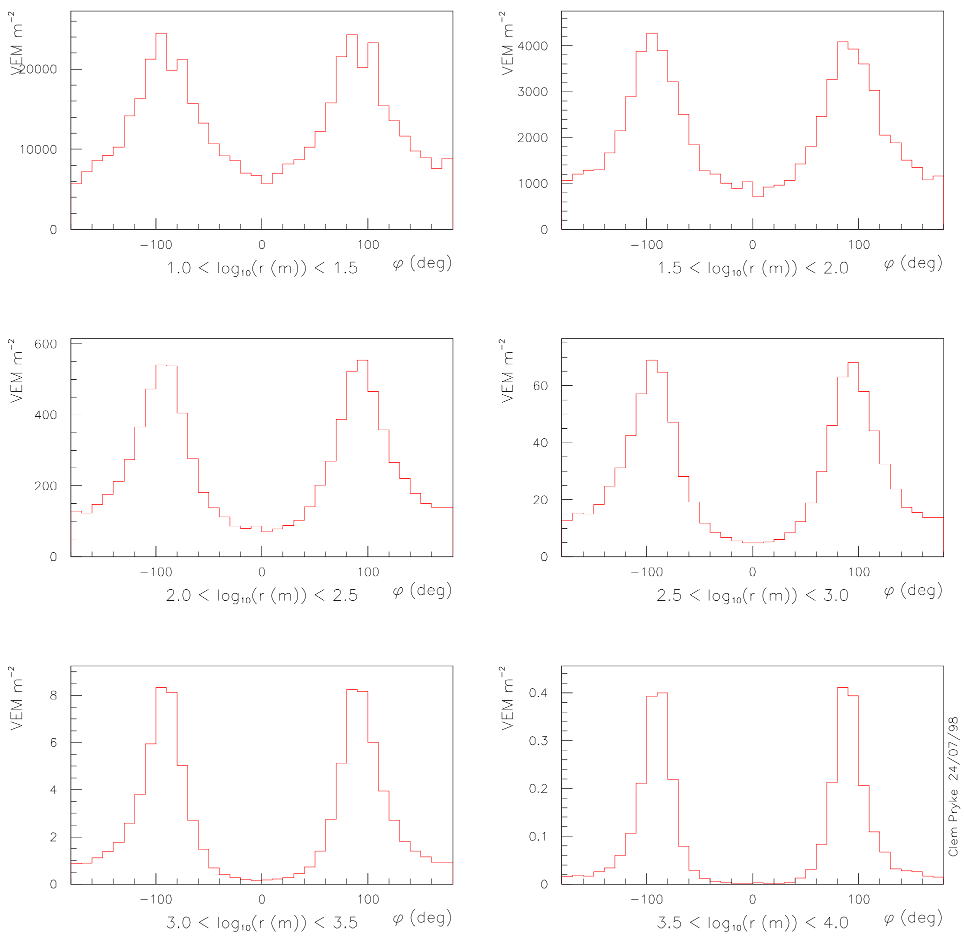

Figure 10: This plot is again similar to figure 7, but with a magnetic field five times actual. A first harmonic fit is now so poor it is not shown.

and longer mean free paths.

We are now in a position to study the dependence of geometrical asymmetry on zenith angle and other shower parameters; the effect is surprisingly large. Figure 12 shows the same quantities in each frame as figure 11, but now plotted versus zenith angle for the first 500 events in the shower library. The relatively tight correlation in gamma and muon plots indicates that the procedure is yielding meaningful results in these cases. It also shows that the energy dependence of the effect is small since a wide energy range is used, and that there is little dependance on primary type. The magnitude of the effect for muons is smaller than for electromagnetic particles, as expected.

The late-to-early ratio of the (observable) total signal decreases smoothly with zenith angle up to ~ 50 deg where the value is $\sim \frac{1}{3}$. At this point it appears to stop decreasing although the scatter of the points becomes large. It can be seen that this turnover and scatter is due to the component of the signal produced by electromagnetic particles. It was initially supposed that the apparent behaviour was caused by ignoring geomagnetic asymmetry when fitting the events. This appears not to be the case; a more sophisticated fit explicitly including the geomagnetic effect shows that it is possible to extract it seperately, but that scatter in the geometric component remains — see appendix A.

Probably at these large zenith angles an increasingly large fraction of the electromagnetic particles are themselves secondary to muons. Thus their spatial distribution starts to reflect that of the muons, and further decrease of the late-to-early ratio is suppressed.

4 Discussion and Conclusions

All air shower arrays of which I am aware base their routine event reconstruction on the assumption that the observations depend only on perpendicular distance from the shower axis. If that assumption is not correct then biases will certainly result. It may be that the induced errors in core position will be stronger than those in inferred primary energy. Only a full Monte Carlo study of a specific experimental configuration can say for sure.

The extent of the asymmetry revealed in this study is much larger than was anticipated. The implications for Auger performance predictions are not yet clear.

Of course one could use a more complex model in event reconstruction

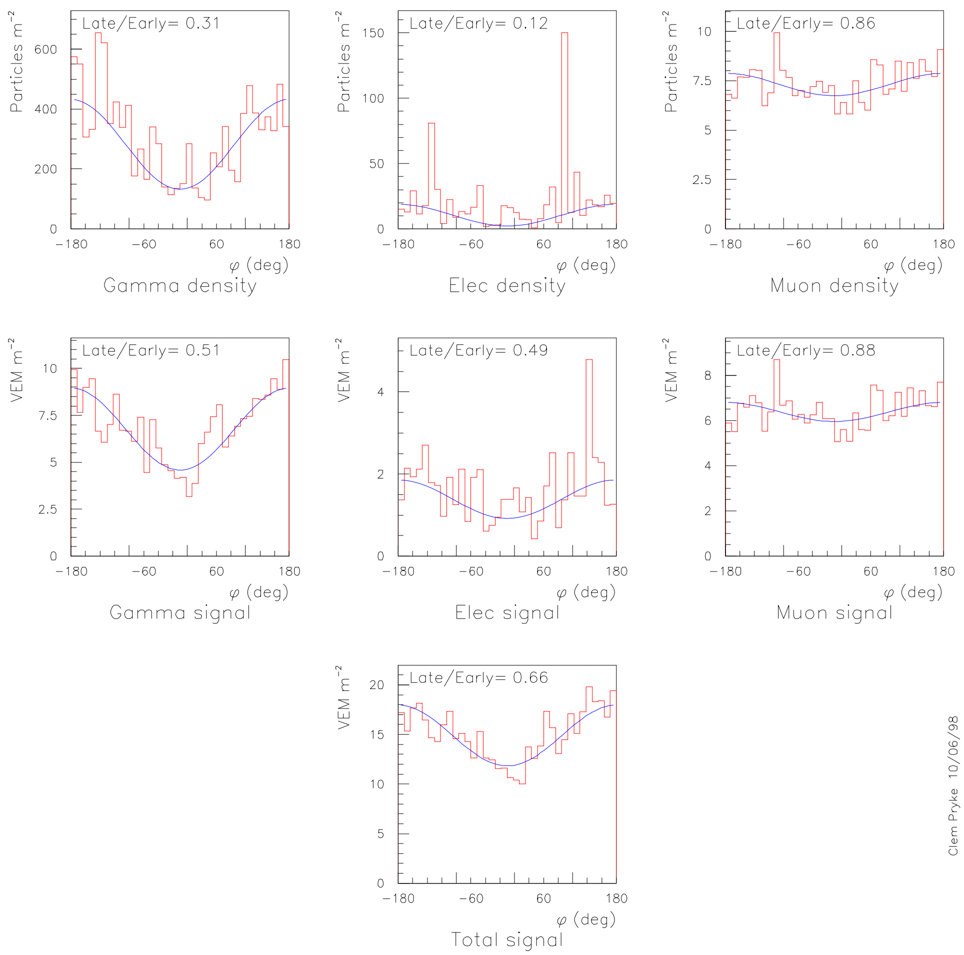

Figure 11: The numerical and signal densities of gammas, electrons and muons versus polar ϕ angle in the shower plane for the first event in the shower library ($\theta = 23$ deg). These plots are for particles within the core distance annulus $3 < \log(r(\mathrm{m})) < 3.5$. A first harmonic fit is shown in each case, with the minimum to maximum ratio indicated.

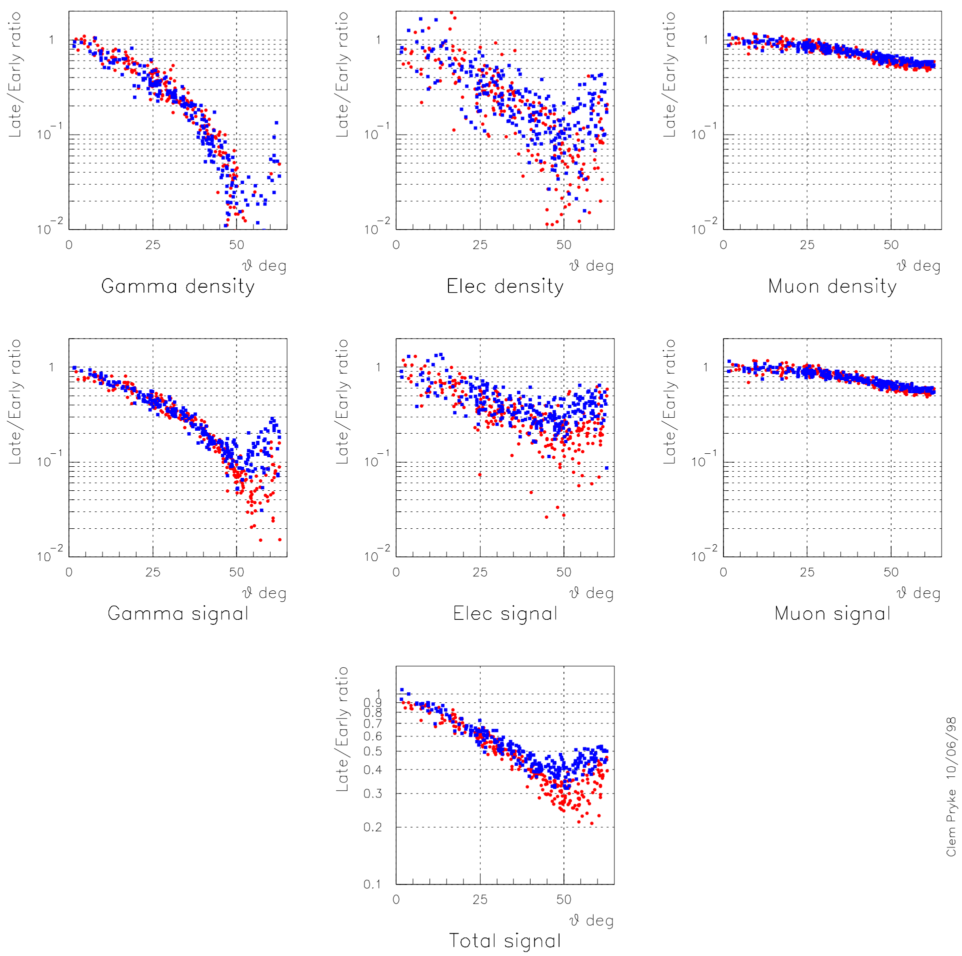

Figure 12: The late-to-early ratios for the same seven cases as figure 11 plotted versus zenith angle θ, for the first 500 events of the shower library. Note that the final plot is the observable quantity, and in that case the vertical range is half that for the other plots. (Red circles are proton events, and blue squares iron.)

to try and account for asymmetry effects. That would require knowledge of their magnitude and dependence on zenith angle etc. This information could come either from shower simulations, such as those performed here, or from measurements with an infill array (or potentially from hybrid data).

However, I do not believe that it will ever be possible to correct perfectly for asymmetry effects. Axial symmetry is a powerful constraint which the fitting procedure exploits to make a measurement from sparse data. I believe that to achieve equivalent resolution when this constraint is removed requires more data (higher detector multiplicity), even if one has a perfect model.

For scintillator detectors the asymmetry would be larger still, since they are more reliant on the rapidly attenuating electromagnetic component.

5 Acknowledgements

I would like to thank Jim Matthews, John Matthews, Lucy Fortson and Joseph Fowler for commenting on a draft of this paper. The Fermilab computing department are thanked for the use of their machines.

A Fitting the Geometric and Geomagnetic Asymmetries Simultaneously

It was assumed above that geometric asymmetry produces a first harmonic modulation of the density of particles in a given core distance annulus. It is necessary to fit only for the mean level and amplitude of this modulation. The phase is known *a priori*; an enhancement where the particles strike the ground earliest, and a depletion where they strike the ground latest.

Geomagnetic asymmetry will produce an additional second harmonic (two peaked) modulation, whose phase will be related to the azimuthal angle of the air shower with respect to magnetic north. If the amplitude of this second effect were large compared to the geometric then fitting with a simple first harmonic function would lead to erroneous results.

To explicitly include the geomagnetic effect the following function is used,

$$\rho = a - b\cos(\theta) - c\cos(2\theta + d),$$

where a is the mean level, b is the amplitude of the geometric modulation, and c & d are the amplitude and phase of the geomagnetic modulation. When the equation is written in this way d appears to be simply the azimuthal angle from which the air shower arrives measured west of magnetic north.

Figure 13 shows the results of fitting this function to the total signal density in the core distance annulus $100 < r < 300$ m. See the figure caption for explanation. It is necessary to move to this closer core distance range to provide sufficient data quality for a 4 parameter fit given the constraints of 10^{-7} thinning; note that even so the geomagnetic effect is always smaller than the geometric. It is clear that the two effects are being correctly separated since the values of c & d are correlated with the shower azimuth angle.

In conclusion it appears that for MOCCA-Sibyll generated showers in the energy range investigated, observed by water Čerenkov detectors, the geometric asymmetry effect is always much stronger than the geomagnetic for zenith angles < 60 deg. The latter is hence safely ignored in the quantitative work in section 3.

References

[1] Geomagnetic field parameters may be determined online for any location at `http://www.ngdc.noaa.gov/seg/potfld/geomag.html`

[2] Hillas, A., "The MOCCA program: MOnte Carlo CAscades", *Proceedings of the 24th International Cosmic Ray Conference, Rome*, **1**, 270 (1995).

[3] Fletcher, R., et al., "Sibyll: An Event Generator for Air Shower Simulations", *Phys. Rev. D* **50**, 5710 (1994).

[4] C. Pryke, *PhD Thesis*, The University of Leeds, (1996). Available from `ftp://aupc1.uchicago.edu/pub/auger/pryke/clp_thesis.ps.gz`

[5] Information on the shower library is available at `http://aupc1.uchicago.edu/~pryke/auger/showsim/`

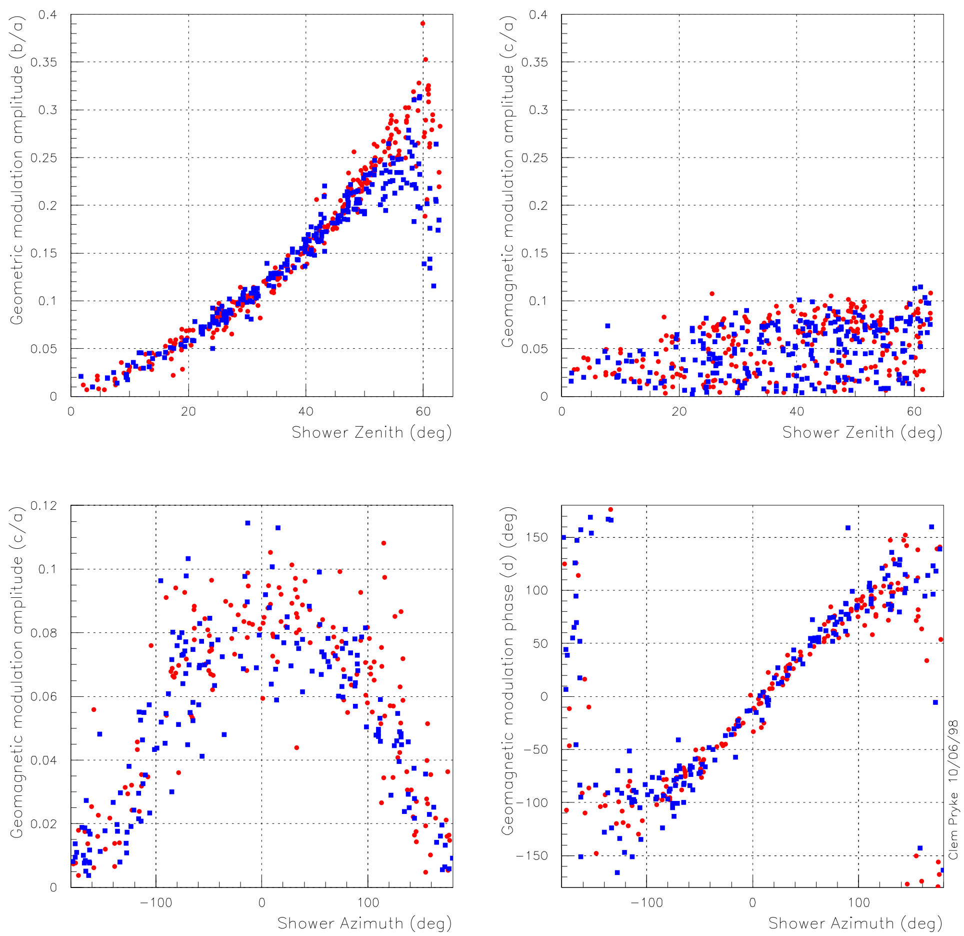

Figure 13: The upper two plots show the fractional amplitude of the geometric and geomagnetic modulations, (b/a) and (c/a), for the full range of zenith angles. At lower left (c/a) again, but now plotted against the shower azimuth; note the strong correlation. At lower right the correlation between the phase of the geomagnetic modulation and the shower azimuth is seen to be good (when the effect is significant). The lower two plots are for zenith angles > 30 deg only. (Red circles are proton events, and blue squares iron.)