# Towards a Parametrization of the Lateral Distribution Function and its Asymmetries in the Surface Detector

Pierre Billoir, Pierre Da Silva
L.P.N.H.E. Paris VI-VII

GAP 2002-073

## 1 Introduction

The response of Cherenkov tanks at ground to an atmospheric shower is a complex superposition of different components. It carries information about the shower through both the integrated signal and its time structure. In this study we only consider the first item, and we want to describe empirically the dependence of the signal on the position of the tank with respect to the shower core: the l.d.f. (*lateral distribution function*), which is actually a function of the distance to core $r$ *and* of the azimuthal direction, because of anisotropies (forward-backward asymmetry, and magnetic distortion for very inclined showers). Here we perform first an average over the azimuth, so that the l.d.f. is a function of $r$ only, for a given shower; the asymmetry is then studied as a sinusoidal modulation.

The shape of the l.d.f. depends mainly on the nature of the primary particle, on the zenith angle $\theta$ of the shower, and on the altitude of the ground; there is also a sensitivity to the density profile of the atmosphere, hence on the meteorological conditions. Here we suppose to be on a standardized "site" as defined in the AIRES shower simulation package (site ElNihuil, Linsley's standard atmosphere), and we restrict the zenithal range to $\cos\theta > 0.2$ ($\theta < 78$ deg).

The aim of this work is to describe the variation of the l.d.f. profile through as few *shape* parameters as possible, that is to find a simple generic expression with enough flexibility to cover our range in $\theta$ for all primaries from proton to iron, and different models for hadronic interaction. It is also intended to be used in the future to extract the l.d.f. from the real events (or at least to constrain it), especially from the hybrid events, by releasing the *shape* parameters in the event fit; this is not yet possible with a good precision with the available data.

The first important information to be extracted from the lateral distribution is the energy of the primary. The standard way foreseen is to first interpolate the value of the signal at a fixed distance from core (1000 m), and then to use a correspondance between this value $S(1000)$ and the primary energy; this correspondence is studied elsewhere[1]. Then a parametrization of the l.d.f. is expected to be precise around this distance, not necessarily close to the axis, or far away.

For practical reasons (existing interface to a detector simulation), we have used only showers simulated with AIRES.

# 2 Simulation Tools

We have used a subsample of the AIRES[2] shower library produced at CCIN2P3 at Lyon[3] (version 2.5, with QGSJET01 and SIBYLL 2.1) at energies ranging from 1 to 100 EeV, and $\cos\theta$ ranging from 0.1 to 1 by steps of 0.1. The ground particle files were input to the detector simulation package *sample_sim*, with a set of tanks defined *ad hoc* (distance to core from 200 to 2500 m, 18 values regularly spaced in azimuthal angle $\psi$ in frontal projection).

The detector response is partly simplified: the signal from a muon or an electron is supposed to be proportional to its path in water; for photons, Compton scattering and pair production are simulated in cascade down to 250 keV. The Cherenkov photons are not traced, the number of photo-electrons is obtained with an overall factor. The value of the signal in VEM is tuned from the simulation of vertical muons in the same conditions. The response to the electromagnetic component was checked to match with DETSIM simulations.

As a consequence, the fluctuations of the signal include only the amount of incoming particles and their energy spectrum, and not the phenomena within the tank and the electronic chain (actually, this internal contribution is not dominant). We do not account for various phenomena which may be important for very inclined showers (hard radiation from energetic muons, direct illumination of PMTs, etc). Globally the distortions due to our simplifications should not exceed 10 %, and have no reason to modify the general features of the l.d.f., nor the comparison between light and heavy nuclei, and between hadronic models.

# 3 Parametrization of the Radial Dependence of the LDF

Depending on the zenith angle, the l.d.f. is a more or less rapidly decreasing function of $r$, with increasing fluctuations. Fig.1 shows that in *log-log* representation, a simple parabolic shape is adequate to describe the average value over the range 200 m to 2.5 km: the precision of the parabolic approximation is better than the fluctuations. For convenience, we choose $r = 1000$ m as origin on the horizontal axis, then we write:

$$y = A + Bx + Cx^2 \quad \text{with} \quad x = \log_{10}(r/1000) \;\; \text{and} \;\; y = \log_{10}(S_{VEM})$$

This has the advantadge of clearly decoupling the *normalization* parameter $A$ (value of $S(1000)$) from the *shape* parameters $B$ and $C$; moreover, $B$ appears to describe the overall *steepness* of the shape, while $C$ measures the deviation from a power law.

The dominant feature (independent of the primary and of the model) is that the slope $B$ increases continuously with $\theta$, while the parameter $C$, always negative, increases also in absolute value. Heavy nuclei give a larger signal at large distance (due to their larger muonic component); at short distance, the situation is less clear and depends on $\theta$ and also on the model. This could be interpreted in the following manner: at very low $\theta$, the electromagnetic component of a proton shower has not yet reached its maximum (the slant depth at ground is too low), while heavy nuclei showers are more "aged'; at large $\theta$, the effect is reversed (the heavy shower is more advanced in its decay than the proton one), but this is compensated by the larger muonic component, which is dominant at very large $\theta$.

Fig.2 shows that in the evolution of the shape parameters $B$ and $C$, we can distinguish two regimes: a first one up to $\theta \simeq 60$ degrees, with a large electromagnetic component, and a second one with muon dominance. It is interesting to note that the differences between light and heavy nuclei appear mainly in the muonic regime for the $S(1000)$ dependence (parameter $A$), while the shape parameters are significatively different in the electromagnetic regime.

# 4 Perspectives on l.d.f. tuning

It is clear that this study needs to be extended to CORSIKA showers and consider other possible influences, especially the dependence on primary energy; the systematic effects due to modelling (e.g. different versions of the same package) have to be evaluated more precisely.

On the other hand, the shape parameters $B$ and $C$ may be constrained by the real events, because $\theta$ is measured with a good precision. A convenient way to do it is to include them in the adjustable parameters of the "core fit" algorithm, in addition to the position $(x_c, y_c)$ of the core at ground and the normalization factor. In principle, knowing the signal in $3+n$ stations is sufficient to determine $n$ additional parameters; in practice, more are needed to have a well constrained fit. As an example[4], a power law $1/r^B$ was applied to the events from Engineering Array with at least 5 stations, with adjustable $B$, and the expected dependence on $\theta$ was observed; however the dispersion of the results do not yet provide a discrimination at the level of the differences seen on Fig.2, for example.

Fitting the parameter $C$ is even more difficult, because this requires, not only a large multiplicity, but also a large "lever arm" in $r$, that is a widely extended shower (for example, events including infill stations or a doublet Carmen-Miranda do not help very much). In practice, this will only be possible at energies above $\sim 10$ EeV, on a larger array; fortunately, the most promising range in $\theta$ for discrimination is around 40-50 degrees, where the ground size/energy ratio is more favourable than for vertical showers.

Of course, the best constraint is expected from hybrid events, which provide an external information on both the core position and the energy; in that case, an event of any multiplicity brings information on the l.d.f.

# 5 Forward-Backward Asymmetry

The origin of this asymmetry is a combination of a progressive longitudinal attenuation of the shower, and a geometrical effect due to the divergence of the particles from the axis (see [5] for a detailed study).

For given primary and zenith angle, at every value of $r$ where tanks have been simulated, an asymmetry coefficient $\alpha$ is fitted on the integrated signals according to a simple sinusoidal dependence:

$$S(r, \psi) = \bar{S}\,(1 + \alpha(r)\,\cos\psi)$$

where $\psi$ is the azimuthal angle in projection onto the shower plane front (with the convention that $\psi = 0$ corresponds to the upstream direction, that is the earliest hits on ground). The results are given in Fig.3 for QGSJET and SIBYLL models, at four different values of $\theta$.

Then $\alpha(r)$ is fitted through a function able to reproduce the main features of the observed dependence: vanishing at $r = 0$ (where both the attenuation and the geometrical effect should go to zero), and reaching more or less rapidly a plateau[1] (this is empirical, and there is no theoretical reason to find an asymptotical value; anyway at large $r$ the statistical precision on data do not allow to conclude) . We choose the following simple expression:

$$\alpha(r) = \alpha_m \tan^{-1}(r/r_0)$$

with only two free parameters: $\alpha_m$ to describe the amplitude of the asymmetry and the distance $r_0$ (here $\sim 500$ m) where it reaches 64 % ($2/\pi$) of its maximum.

Let us point out that the combination of shower-to-shower variations and statistical fluctuations of the signal in a tank are not negligible compared to the amplitude of the asymmetry, then a more precise parametrization would not really help to extract the best information from an event.

Fig.4 shows the dependence on the asymmetry to the zenith angle $\theta$. As expected, it increases with $\theta$ as long as the shower is dominated by the electromagnetic component, and after a maximum around 50 degrees, it goes back to low values for quasi-horizontal showers.

There is an interesting difference between showers induced by light and heavy nuclei, especially in the region $\theta = 40$ to 60 degrees, where the acceptance is large. However this the difference between $p$ and $Fe$ is similar to the difference between QGSJET and SIBYLL (although we have used recent versions which, in principle, are less discrepant that further ones); moreover this difference is less than the effect of fluctuations on a single event. As a conclusion, the measurement of the asymmetry may give a discriminant variable, but only on a statistical basis, and provided modelling errors are better understood.

# 6 Conclusion

Using simulated events, it is possible to find a simple log-parabolic parametrization of the l.d.f. (lateral distribution function) of the tank response, as a function of the distance to the shower axis (averaging over the azimuthal angle), in the range of practical interest (200 to 2500 m in this study). This function is described by three coefficients: the first one is related to the signal at a reference distance (here 1000 m),

[1]Clearly this behaviour cannot be explain from a longitudinal attenuation of the shower, which would imply a regularly growing asymmetry.

the second one represents the slope at this distance, and the third one measures the deviation from a pure power law.

These coefficients have a characteristic dependence on the zenithal angle, and also on the nature of the primary: with large multiplicity events, they may be fitted together with the core position to provide discriminating variables for the identification task.

The asymmetry may be described by a smooth (but non-linear) function of the distance to core. Its amplitude depends on the zenith angle, with a maximum around 50 degrees, and slight differences between light and heavy nuclei.

Both the radial shape and the asymmetry are sensitive to modelling errors. It would be very useful to study more extensively these systematic effects, and also to analyze in the same way ground particle files generated with CORSIKA, and, of course, to examine whether the real events are compatible with the simulated results. A preliminary approach, showing a general agreement, was included in [4], but a precise study requires a large statistics of events with a large extent, and if possible hybrid, to get rid of the uncertainty on the core position; this is not yet available, and will not be in the next future.

# References


[1] P. Billoir: Parametrization of the Relation between the Primary Energy and S(1000) in the Surface Detector, GAP-2002-075

[2] S. J. Sciutto: AIRES, users guide and reference manual, vers. 2.2.0, GAP-99-020
S. J. Sciutto: AIRES, a minimum document, GAP-97-029

[3] S. J. Sciutto, FNAL shower library (private communication)

[4] P. Billoir: Reconstruction of first year EA events from the Surface Detector, GAP-2002-044

[5] X. Bertou, P. Billoir: On the Origin of the Asymmetry of Ground Densities in Inclined Showers, GAP-2000-017 P. Billoir, X. Bertou, P. Da Silva: Checking the Asymmetry of the Surface Detector Signal, GAP-2002-074

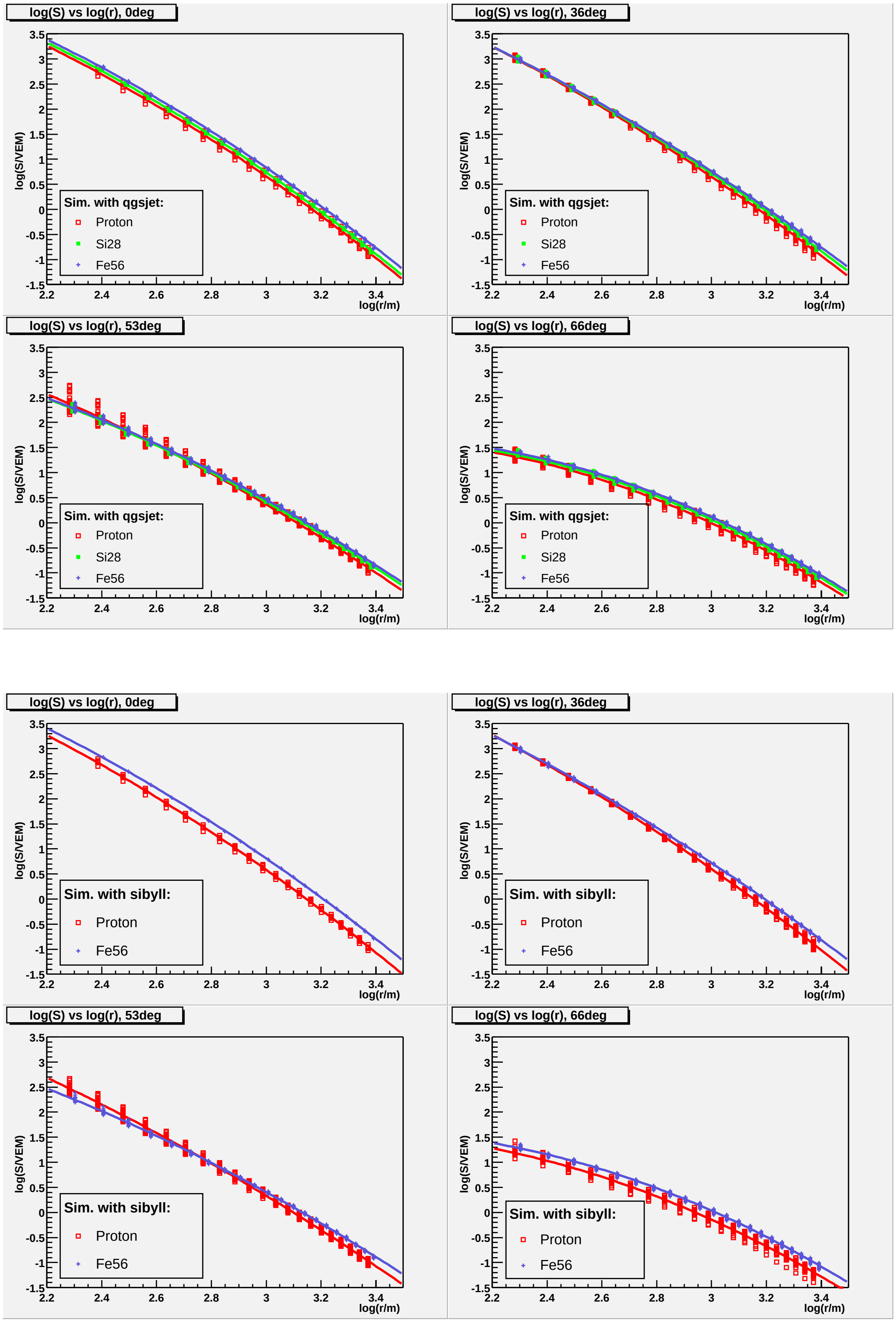


Figure 1: Integrated signal in tanks as a function of the distance to core (averaged over azimuthal angle), at different zenith angles of the shower, using QGSJET01 (top) or SIBYLL 2.1 (bottom) as model for hadronic interactions.

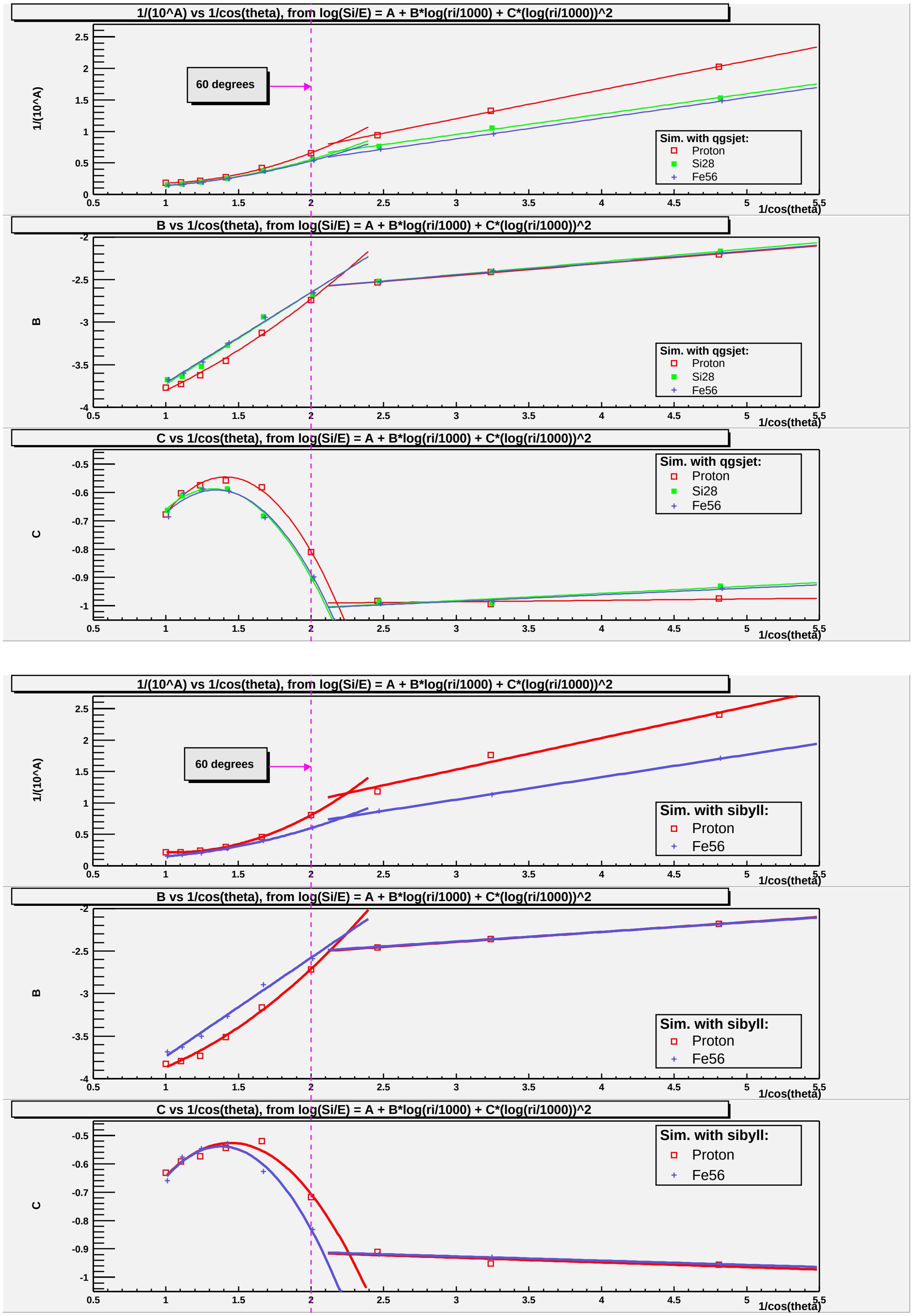


Figure 2: Dependence of the shape parameters of the l.d.f. on the zenith angle, for different primaries, using QGSJET01 (top) or SIBYLL 2.1 (bottom) for hadronic interactions. The curves are given to guide the eye.

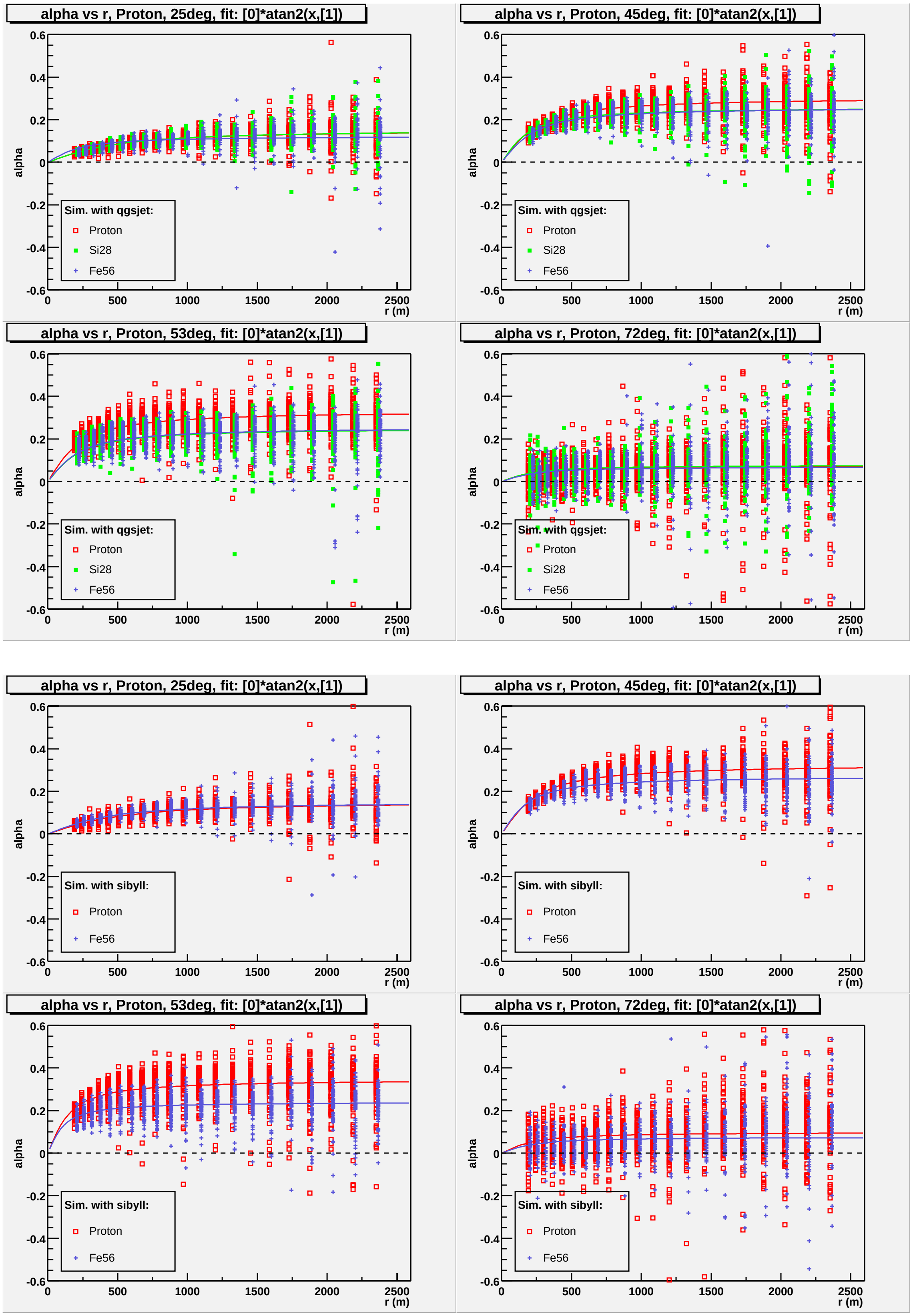


Figure 3: Asymmetry of the l.d.f. as a function of the distance to core, for different primaries, using QGSJET01 (top) or SIBYLL 2.1 (bottom) for hadronic interactions. The curves are the results of the fit with an *arctan* function.

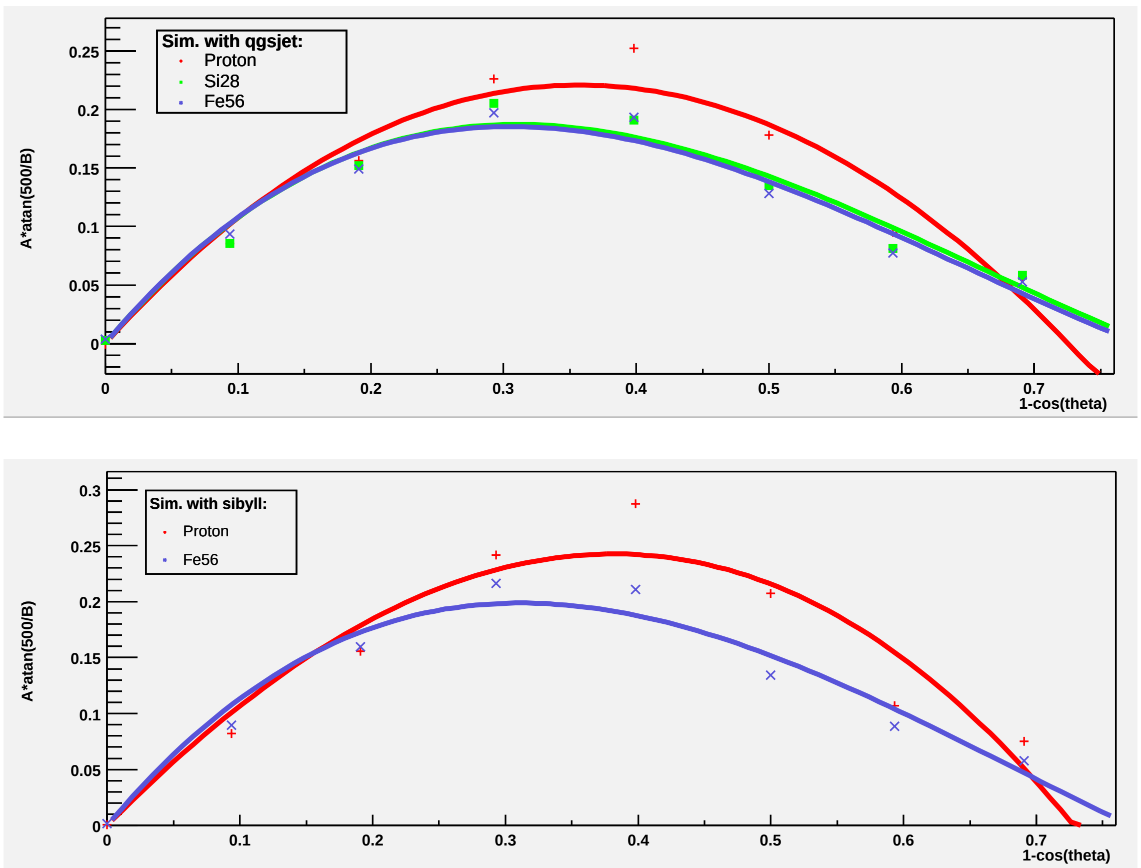


Figure 4: Asymmetry of the l.d.f. at 500 m from the core, as a function of the zenith angle, for different primaries, using QGSJET01 (top) or SIBYLL 2.1 (bottom). The curves are a fit to guide the eye.