Time asymmetries in extensive air showers: a novel method to identify UHECR species

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Abstract. The azimuthal asymmetry in the time distribution of shower particles detected by a ground array offers a new possibility for the determination of the mass composition. The dependence of this asymmetry on atmospheric depth shows a clear maximum at a value that is correlated with the primary mass. In this work a novel method to determine mass composition based on these features of the ground signals is presented.

Keywords: asymmetries, mass composition, rise-time

I. INTRODUCTION

The mass composition of ultra high energy cosmic rays (i.e. over around 10^{18} eV) is a crucial ingredient for understanding their origin, acceleration mechanisms and propagation. In this energy range the properties of cosmic rays are deduced from the features of the extensive air showers generated in the atmosphere. Basically two types of detectors are used: ground arrays which sample the tail of the shower and fluorescence telescopes which register directly its longitudinal development.

The measurement of the primary mass at the highest energies is very difficult due to the large fluctuations resulting from the statistical nature of the shower development. Furthermore, the interpretation of data relies in extrapolations of hadronic interaction models at energies much larger than those studied in accelerator experiments.

As is well known the features of the shower development depend on the primary mass. While fluorescence telescopes are able to register directly the longitudinal development of the shower and therefore measure the shower maximum depth $X_{\max}$, most surface observables sensitive to composition provides a snapshot of the shower development and thus, they are correlated with both $X_{\max}$ and the observation depth.

In ground array experiments the shower properties are reconstructed by projecting the signals registered by the detectors into the shower plane (see Figure 1) and thus, neglecting the further shower evolution of the late regions. As a consequence, for inclined showers, the circular symmetry in the signals of surface detectors is broken. This results in a dependence of the signal features (both size and time structure) on the azimuth
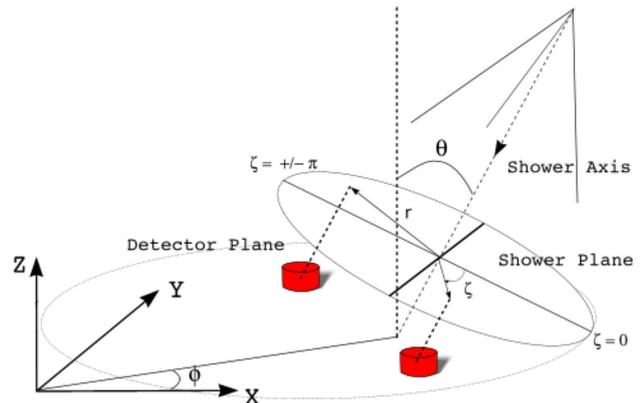

Fig. 1. Schematic view of the shower geometry. The vertical projection of the incoming direction into the shower plane ($\zeta = 0$) defines two regions, "early" ($\frac{-\pi}{2} < \zeta < \frac{\pi}{2}$) and "late".

angle in the shower plane, mainly due to the different amount of atmosphere traversed by the particles [1].

The asymmetry in the risetime[1] $t_{1/2}$, is related to the stage of the shower development [2]. Thus, for a given primary energy, this time asymmetry depends on the zenith angle of the primary cosmic ray θ in such a way that its behavior versus $\sec\theta$ is reminiscent of the longitudinal development of the shower. As will be shown below, this "longitudinal development of the asymmetry" is strongly dependent on the nature of the primary particle.

The technique discussed here can be applied in very large surface arrays provided with particle detectors with high time resolution. Presently the Pierre Auger Observatory which fulfils these requirements, is employing this technique [3]. The analysis described in this work is based on Monte Carlo simulations carried out with the code AIRES [4] using the hadronic interaction models QGSJETII(03) [5] and SIBYLL 2.1 [6]. The simulated showers were used as input in the detector simulation code of the Pierre Auger Observatory and finally reconstructed using for both tasks the offline software of this experiment [7].

More details on this novel method can be found in [8].

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[1] time to reach from 10% to 50% of the total integrated signal.
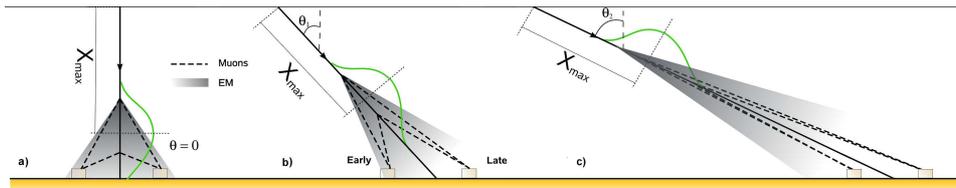
Fig. 2.   Schematic view of shower development when arriving at three different zenith angles.

II. ASYMMETRY IN THE TIME STRUCTURE AS AN INDICATION OF SHOWER EVOLUTION

The relation between time asymmetry and shower evolution is sketched in Figure 2, where three different scenarios are presented for a shower with a given $X_{\max}$ value, arriving at three different zenith angles. The attenuation (early-late) of the electromagnetic EM component depends on the difference in the path travelled by particles to reach the detector stations. In case (a), i.e. vertical shower, there is no difference in the paths of the EM component so there is no asymmetry. As the zenith angle increases (case b) the difference in the attenuation of the EM component due to different traveled paths increases and, as a result, early-late asymmetry appears[2]. At very large zenith angles (case c) the EM component is strongly absorbed before reaching the detector. In this case, the asymmetry decreases with θ since the larger is the angle the smaller is the contribution of the EM component. Note that the muonic component is basically asymmetry free. Then for a given zenith angle the asymmetry gives information of the stage of development of the shower. According to the above arguments, a plot of asymmetry against $\sec\theta$ is expected to have a maximum which is correlated with the longitudinal shower evolution.

A generic time function which, for vertical showers, depends on atmospheric depth t and core distance r $\tau(r,t)$ (e.g. the signal risetime) becomes for inclined showers with zenith angle θ

$$\tau(r,t) \rightarrow \tau(r,t'(\zeta,\theta)) \qquad (1)$$

where r is measured in the shower plane and t' is the depth traverse by particles which not only depends on θ but also on the azimuth angle in the shower plane. As can be demonstrated, for a given zenith angle, a Taylor expansion up to first order of τ around the corresponding slant depth $t_s = t\sec\theta$ gives the simple expression

$$\tau(r,\zeta) = a + b\cos\zeta \qquad (2)$$

with

$$a = \tau(r,t\sec\theta); \qquad \frac{b}{a} = B\frac{\partial\ln\tau}{\partial\ln t'}\Big|_{t_s} \qquad (3)$$

The asymmetry factor b/a which depends on t_s, can be used as a measure of the logarithmic variation of τ with slant depth. This parameter is an indicator of

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[2]At zenith angles smaller than 30° there is an additional geometrical effect [9]

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the shower evolution and hence it provides a measure of the composition of the primary particle. The dependence of the asymmetry factor b/a with $\sec\theta$ allows one to find new observables useful for determining the mass composition, as will be shown in Section III.
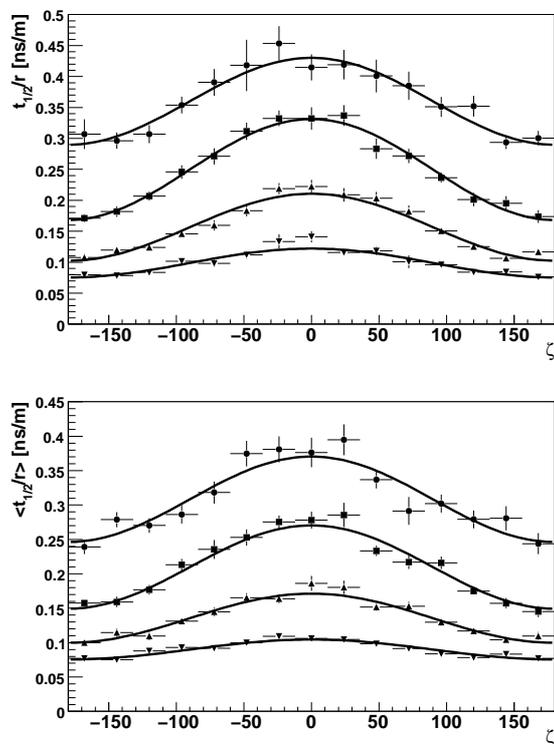

Fig. 3.   Risetime versus azimuth angle in the shower plane for primary energy of 10^{19} eV and different zenith angles for proton (upper panel) and iron showers (lower panel).

III. MASS SENSITIVE PARAMETERS

A MC sample of 2×10^4 showers initiated by protons and Fe nuclei in the energy range $18.5 < \log(E/\text{eV}) < 20$ and zenith angle $32° < \theta < 63°$ has been used for this analysis. Due to the intrinsic fluctuations in extensive air showers and the limited sampling of the shower front recorded by a surface detector, it is not possible to obtain the mass composition in a shower by shower basis. That is, instead of measuring the asymmetry in individual showers, the mean value of various asymmetry parameters defined below are calculated from all showers in a certain interval of energy and zenith angle.

A. The longitudinal asymmetry development

For each primary type, events are grouped in bins of reconstructed energy and $\sec\theta$ values. For each group, the mean value and the standard deviation of the $t_{1/2}/r$ distribution for those stations (passing certain quality cuts [8]) within a given ζ interval is calculated[3]. For each (E, θ) bin, a fit of $< t_{1/2}/r >$ to a linear cosine function of ζ (equation 2) provides the asymmetry factor b/a. Figure 3 shows as an example, the result for showers with E = 10^{19} eV and four zenith angles, 32°, 45°, 53° and 60° (from top to bottom).

For each primary type and energy interval the dependence of the asymmetry factor on $\sec\theta$ has been studied. In all cases the plot b/a versus $\ln(\sec\theta)$, i.e. the asymmetry longitudinal development, is quite symmetric and shows a clear maximum. Figure 4 (upper panel) shows as an example the results for both primaries at 10^{19} eV.

This longitudinal development of the asymmetry can be described by means of three parameters calculated by fitting a normal function to the values of b/a in bins of $\ln(\sec\theta)$. These parameters, represented in Figure 5 (lower panel) are: *XAsymMax*, the position of the maximum asymmetry, i.e. the $\sec\theta$ value for which b/a

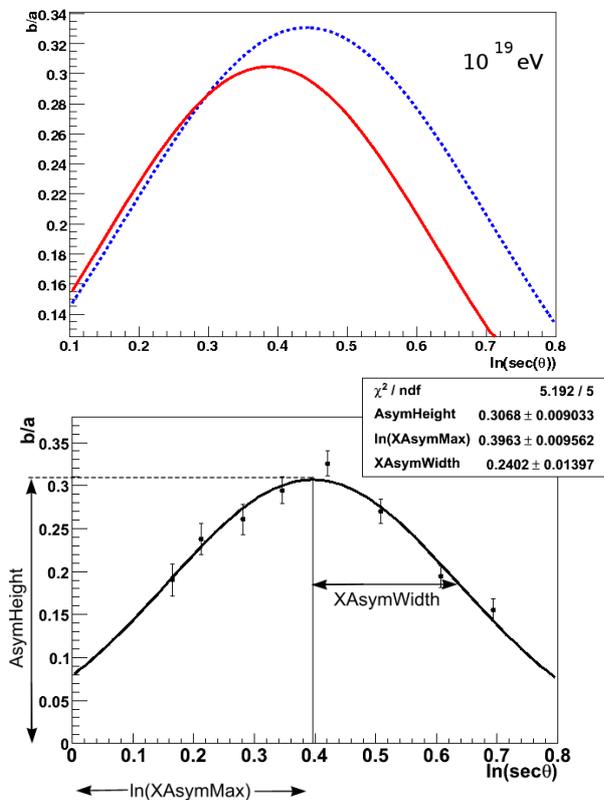[3]notice that risetime grows nearly linear with the core distance

Fig. 4. Asymmetry longitudinal development. In the upper panel the result for 10^{19} eV primary energy for protons (dashed line) and Fe nuclei (solid line) is shown. In the lower panel the separation parameters are defined.

maximises; *AsymHeight*, the height at maximum, i.e. the maximum b/a value, and *XAsymWidth*, the half width at half maximum of the Gaussian function.

B. Energy dependence and hadronic models

The values of the parameters defined above have been calculated for proton and Fe showers as a function of the primary energy using both hadronic interaction models. In Figure 5 the result for *XAsymMax* is shown. The error bars come from the fitting uncertainties. *XAsymMax* grows linearly with $\log E$. The corresponding linear fits (continuous lines) of both primary types are clearly separated, thus allowing discrimination of heavy and light primaries. On the other hand, we have found that the *AsymHeight* parameter exhibits a dependence with $\log E$ which nearly follows a parabolic function. In principle this parameter could be also used for separation purposes. Finally, *XAsymWidth* is nearly independent on primary energy with a value very similar for both primaries and therefore this parameter does not allow separation between primaries.

There are indications that the number of muons predicted by simulations is smaller than that found experimentally [10]. This uncertainty imposes restrictions to the reliability of parameters which are sensitive to the muon content of the shower. We have carried out a test to check the dependence of the above separation parameters with the muon number. For this purpose we have compared the above results with those obtained after increasing by a factor up to f=1.6 the muon content The result of such muon test showed that while *XAsymMax* is weakly dependent on f (e.g., for $f = 1.6$ *XAsymMax* is reduced by about 1%), the *AsymHeight* parameter turns out to be very sensitive to a enhancement of the muon content. As a consequence, *XAsymMax* turns out to be the most useful asymmetry parameter for discrimination purposes.

As can be seen in Figure 5, predictions for iron do not show a remarkable dependence on the hadronic interaction model. On the contrary, there is a clear difference for proton primaries, particularly at high energies. This
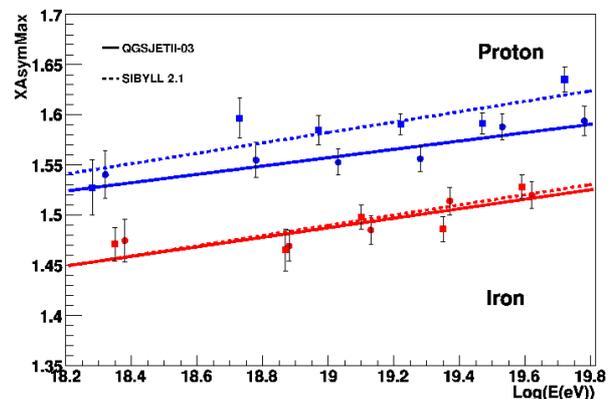

Fig. 5. *XAsymMax* parameter versus $\log E$ for proton and Fe showers as predicted by both hadronic interaction models.

is also a feature of the elongation rate plots where a similar behaviour at high energies is observed for both models [11].

IV. ASYMMETRY PARAMETERS AND DEPTH OF SHOWER MAXIMUM

As is well known, $X_{\max}$ is the main observable related to composition in fluorescence measurements. Thus, it is desirable to study the correlation between our asymmetry mass sensitive parameters measured with a surface detector and the position of shower maximum. To this end, the steps described above were repeated but instead of grouping separately p and Fe events by primary energy, they were grouped in bins of $X_{\max}$. The $X_{\max}$ values used in these plots, are those from the simulated showers.
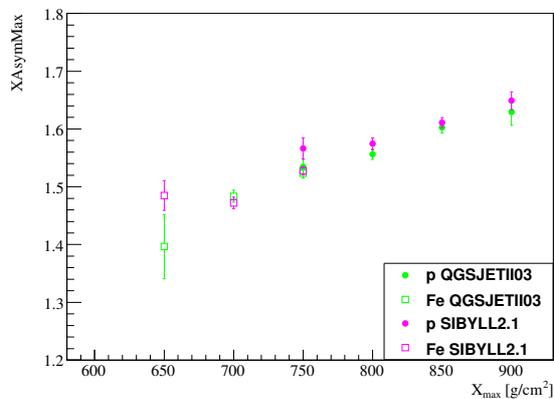

Fig. 6. *XAsymMax* parameter versus the shower maximum depth for both primaries and interaction models.

The correlation of the asymmetry parameters with $X_{\max}$ has been studied. As a result we have found that *XAsymMax* and *AsymHeight* exhibit a strong correlation with the shower maximum depth. In Figure 6 the result for *XAsymMax* has been represented. The correlation is found to be the same for both primaries and nearly independent on the assumed hadronic interaction model. This is an encouraging result reaffirming that the observed azimuthal asymmetry is a reliable mass estimator, as far as accurate models to describe extensive air showers are available. Certainly, the correlation of the surface parameters with the position of shower maximum might be also useful to provide a measurement of $\langle X_{\max}\rangle$ from a surface detector.

V. CONCLUSIONS

A novel method to determine the mass composition of primary cosmic rays has been developed using the azimuthal asymmetry in arrival time distribution of secondary particles at a given observation level. The approach relies on statistical grounds and thus provides a mean mass composition of a set of showers at a given energy.

The main idea behind the method is to reconstruct a longitudinal development of the observed asymmetry which is reminiscent of the longitudinal development of the extensive air shower. A detailed analysis using the risetime of the signal in water Cherenkov detectors for the case of the Pierre Auger Observatory was presented. It was shown that both the atmospheric depth corresponding to the position of maximum asymmetry and the value of the maximum asymmetry are sensitive to primary mass. These parameters measured by the surface detectors were shown to correlate with the position of shower maximum, $X_{\max}$. In addition the *XAsymMax* parameters is nearly insensitive to possible uncertainties in the muon content of the shower.

This method has been validated using hypothetical data samples corresponding to pure proton, pure iron and a mixed composition [8]. Systematic uncertainties affecting the determination of primary composition were investigated. As expected, the dominant source of uncertainties comes from the lack of knowledge of hadronic interaction models, which amounts to $\approx 14\%$ out of a total of 18% in the estimation of Fe fraction [8]. The analysis indicates that at the event rate collected by the Pierre Auger Observatory, good separation of heavy and light elements can be achieved with present data, for energies below 10^{19} eV, while at higher energies at least one order of magnitude more data would be needed.

REFERENCES

[1] M. T. Dova, L. N. Epele and A. G. Mariazzi, Astropart. Phys. **18**, 351 (2003).
[2] AUGER Collaboration (M. T. Dova for the Collaboration), Proc. 28th International Cosmic Ray Conference,Tsukuba, Japan, Editors: T. Kajita, Y. Asaoka, A. Kawachi, Y. Matsubara and M. Sasaki, Universal Academy Press, Inc. Tokyo, Japan, **HE**, 369-372 (2003) [arXiv:astro-ph/0308399].
[3] H. Walhberg *et al.* (The Pierre Auger Collaboration) These Proccedings.
[4] S.J. Sciutto, AIRshower Extended Simulations (1999) [arXiv:astro-ph/9911331]. http:/wwww.fisica.unlp.edu.ar/auger/aires/
[5] S. Ostapchenko, Nucl. Phys. Proc. Suppl. **B151**, 143 (2006).
[6] R. Engel, T. K. Gaisser, T. Stanev, Proc. 26th International Cosmic Ray Conference, Utah, USA, **1**, 415-418 (1999) [arXiv:astro-ph/0706.1495v1].
[7] S. Argiro et al, Nucl. Instrum. Meth. A **580**, 1485 (2007).
[8] M.T.Dova *et al.* Astroparticle Physics 31 (2009) 312.
[9] X. Bertou & P. Billoir, paper in preparation.
[10] A. Castellina *et al.* (The Pierre Auger Collaboration) These Proccedings.
[11] M. Unger et al., Proc. 30th International Cosmic Ray Conference, Merida, Mexico (2007) [arXiv:astro-ph/07061501].