Prospects for Separating UHECR Species Using Asymmetries in Time Distributions

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***Abstract*— Azimuthal asymmetries in time structure and signal size have been observed for the first time in non vertical showers at the Pierre Auger Observatory. The asymmetry in time distributions offers a new possibility for the determination of the mass composition. Recent studies have demonstrated that the dependence of the asymmetry parameter in the rise-time and fall-time distributions with atmospheric depth shows a clear peak, which is correlated with composition of the primary particle. In this paper a Monte Carlo study of the sensitivity of this novel method to separate UHECR species is presented.**

I. Introduction

The composition of ultra high energy cosmic rays (UHECR: $E > 10^{18}$ eV) is still unknown. Its knowledge would greatly help to solve the question of the origin of UHECR. Therefore composition is one of the main objectives of the Pierre Auger Observatory. In the case of inclined showers produced by cosmic rays, the circular symmetry observed in the signals collected by the surface detectors is broken. Evidence of the azimuthal asymmetries in the signal size were first observed at Haverah Park [1] and the first observation of asymmetries in time distributions of the ground detector signals were found in the Pierre Auger Observatory [2]. When the shower hits the surface detector, the particles at different azimuth angles have travelled different paths producing the observed asymmetry. The asymmetry in time distributions offers a new possibility for primary composition determination, because its magnitude is strongly dependent on the muon to electromagnetic ratio. We have studied the sensitivity of the Pierre Auger Observatory for mass separation using asymmetries in time distributions of simulated proton and iron initiated showers.

II. Asymmetry, shower evolution and mass composition

The most important mass-sensitive shower parameters are related with shower development and then, are correlated with X_{max} and atmospheric depth. The time distribution of the signals contains implicitly the information of the shower development. Therefore, it is natural to expect a dependence of the mean values of the time distributions, and the corresponding asymmetries observed on atmospheric depth [3].

In fig. 1 we show a sketch of a non-vertical shower hitting the surface detector. It is clear that the shower is in different stage of development in the "early" (red) region as compared with the "late" (blue) one. The traces of four different stations of a real event recorded by the surface detector of the Pierre Auger Observatory are shown. The stations on the right (left) correspond to two different positions in the "early" ("late") region. We can see that the time features of the signal are different in the two regions, even for similar core distances. The asymmetry in time distributions is due to the different ratio of muonic over electromagnetic component within the trace. The first portion of the signal is dominated by the muon component that tends to arrive earlier and over short period of time, while the electromagnetic particles are spread out of time.

The observed azimuthal asymmetry is also an indicator of composition because it is directly related to the gradual absorption of the electromagnetic component in the "late" region with respect to the "early" region, changing the ratio of the muonic to electromagnetic components.

There is a dependence of the atmospheric slant depth with the azimuthal angle ζ for inclined showers as it was proposed in [3]. Considering that the azimuth angle correction is small, we can treat this dependence using Taylor expansion up to first order around $t \sec\theta$, where t is the vertical depth and θ the zenith angle, that is, the slant depth is a linear function of $\cos\zeta$.

If we call $t' = \int_h^\infty \rho_{atm}(z)dz'$ the atmospheric slant depth, with z' along the shower axis, then:

$$\begin{aligned} t'(\zeta) &= t\sec\theta(1 + B_0\tan\theta\cos\zeta) = t_s + \Delta t_s(\zeta) \\ t_s &= t\sec\theta \\ \Delta t_s(\zeta) &= t_s B_0 \tan\theta\cos\zeta \end{aligned}$$

where $\zeta = 0$ for the incoming direction of the shower.

In vertical showers, a generic time distribution $\tau(r,t)$ will be function of t, the atmospheric depth along the shower axis, and r, the distance to the shower axis in the shower plane (core distance). In the case of inclined showers, $\tau(r,t) \rightarrow \tau(r, t'(\zeta,\theta))$. Performing a Taylor expansion around t_s, we obtain:

$$\tau(r,\zeta) = \tau(r,t_s)(1 + \frac{\partial \log\tau}{\partial \log t'} |_{t_s} B\cos\zeta + \cdots) \qquad (1)$$

which can be approximated as $\tau(r,\zeta) = a + b\cos\zeta$. The asymmetry factor $\frac{b}{a}$ which depends on the core distance and

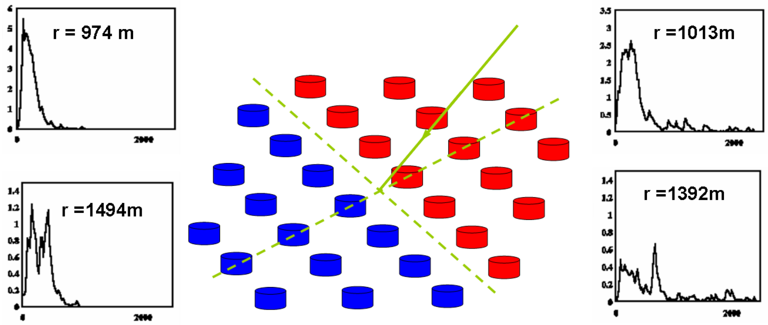

Fig. 1. Sketch of a shower hitting the detector plane. Examples of traces recorded by the surface detector of the Pierre Auger Observatory

the atmospheric depth, is a measurement of the logarithmic rate of change of the variable considered:

$$\begin{aligned}\tau(r,\zeta) &= a + b\cos\zeta\\ a &= \tau(r, t\sec\theta)\\ \frac{b}{a} &= B\frac{\partial\log\tau}{\partial\log t'}\,|_{t_s}\end{aligned}$$

III. Monte Carlo Analysis

For the study of the sensitivity of the Pierre Auger Observatory, we have used proton and iron initiated showers generated with AIRES 2.6.0/QGSJET01 with primary energies 10^{19}, $10^{19.5}$ and 10^{20} eV and zenith angles between 0^0 and 60^0. The detector response of the Pierre Auger Observatory was simulated using the official Offline v2r0 tool, with the SDSim module (default configuration).

We have analyzed two distributions, "rise-time" defined as the time between 10% and 50% of the integrated signal, and "fall-time" defined as the time between 50% and 90% of the integrated signal. The dependence of the mean value of these distributions, divided by the core distance, with azimuth angle was fitted using the functional dependence, $\tau = a + b\cos\zeta$. In fig. 2 and 3 we show as an example, the results for 10^{19} eV proton and iron showers. The fit was performed for each primary species, energy and zenith angle, for all stations between 500 m $<$ R $<$ 2000 m from the core.

The azimuthal asymmetry is clearly seen, and shows the expected behavior, since more extended pulses (larger "rise-time" and "fall-time") in the "early" region ($\zeta = 0^0$) correspond to earlier stage of shower development as compared with the "late" region ($\zeta = \pm180^0$).

We have studied the behavior of the asymmetry factor with $\sec\theta$ (proportional to slant depth). The curve $\frac{b}{a}$ versus $\ln\sec\theta$ show a clear peak, which is in different position for proton and iron showers. To determine the position of the maximum a fit to a gaussian function has been performed. Examples of these curves with their corresponding fits are presented in fig. 4, asymmetry factor for "fall-time" 10^{19} eV iron showers and in fig. 5, asymmetry factor for "rise-time" 10^{20} eV proton showers.

The position of the maximum, $\sec\theta_{max}$, as a function of primary energy is shown in fig. 6 and 7 for proton and iron primaries for "fall-time" and "rise-time". Clearly the corresponding slant depth of this maximum is $X_{asymax} = t\sec\theta_{max}$. The vertical bars show the errors of the fit. The position of the maximum of the asymmetry factor is different for different primaries and allows then to help separating primary species.

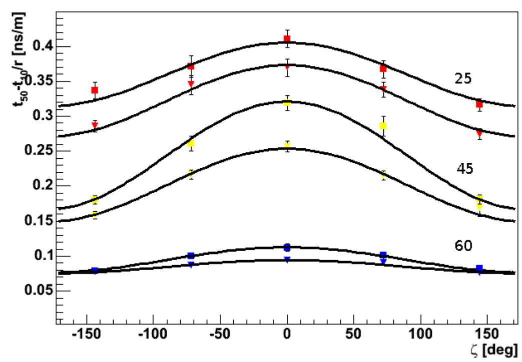

Fig. 2. Mean value of the "rise-time" divided by the core distance for proton (squares) and iron (triangles) , 10^{19} eV showers. From top to bottom, theta 25^0, 45^0 and 60^0

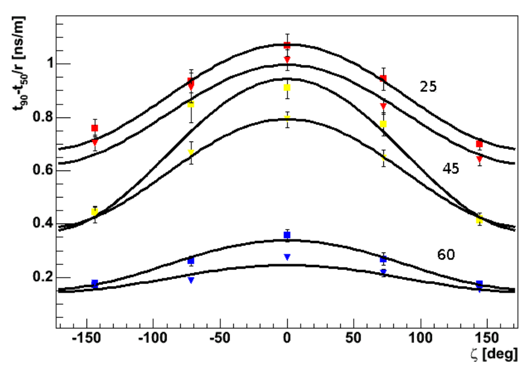

Fig. 3. Mean value of the "fall-time" divided by the core distance for proton (squares) and iron (triangles) , 10^{19} eV showers. From top to bottom, theta 25^0, 45^0 and 60^0

IV. Conclusions

The information recorded by the surface detector of the Pierre Auger Observatory is extremely rich for composition

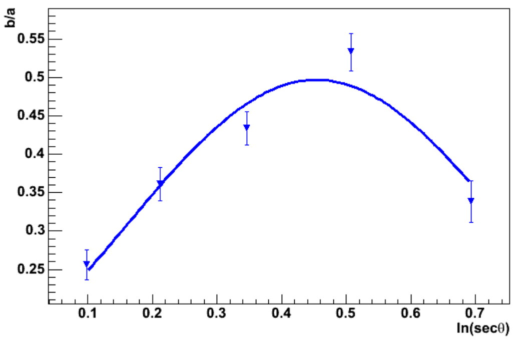

Fig. 4. Asymmetry factor $\frac{b}{a}$ as a function of $\ln \sec\theta$ corresponding to fall-time, for 10 EeV, iron showers.

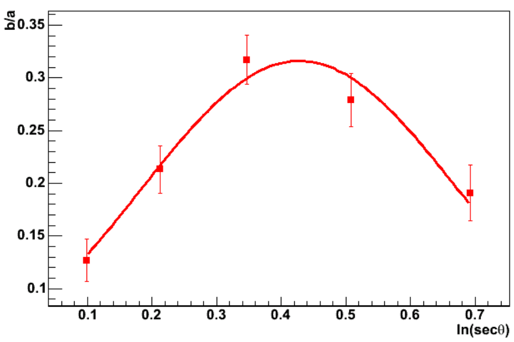

Fig. 5. Asymmetry factor $\frac{b}{a}$ as a function of $\ln \sec\theta$ corresponding to rise-time, for 100 EeV, proton showers.

studies, in particular, we have shown that the observed azimuth angle asymmetries in showers with zenith angles lower than 70^0, which is a unique feature of the Pierre Auger Observatory, can be used for mass separation.

We have analyzed the asymmetry of two distributions, "rise-time" and "fall-time" which are sensitive to the presence of the electromagnetic and muonic components of the shower and thus, to primary composition. We study the dependence of the asymmetry parameter with the atmospheric depth ($\sec\theta$) using Monte Carlo simulations. As a result of this analysis a new observable for primary discrimination is presented. A clear peak appears in the plot of the asymmetry factor with atmospheric depth, the position of which is sensitive to primary mass.

With high statistics sample of inclined showers we expect to be able to obtain information on the primary composition with good precision using the method described in this work.

We have applied the method to "rise-time" and "fall-time" distributions but it could also be applied to some other pulse shape parameters.

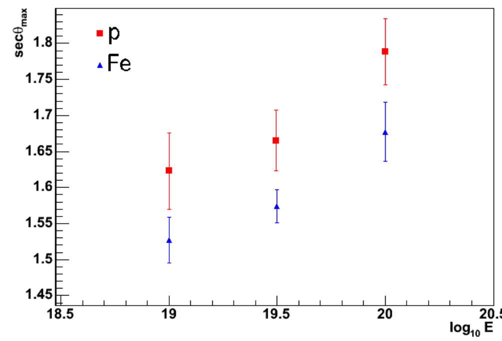

Fig. 6. Position of the maximum of the asymmetry for fall-time distributions, $\sec\theta_{max}$, as a function of the $\log_{10} E$ for proton (squares) and iron (triangles) showers

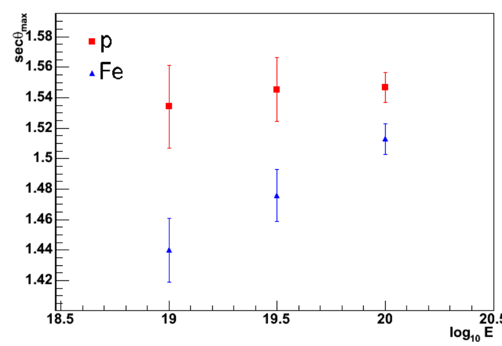

Fig. 7. Position of the maximum of the asymmetry for rise-time distributions, $\sec\theta_{max}$, as a function of the $\log_{10} E$ for proton (squares) and iron (triangles) showers

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