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Hinting at primary composition using asymmetries in time distributions

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Evidence of azimuthal asymmetries in the time structure and signal size have been found in non-vertical showers at the Pierre Auger Observatory. It has been previously shown that the asymmetry in time distributions offers a new possibility for the determination of the mass composition. New studies have demonstrated that the dependence of the asymmetry parameter in the rise-time and fall-time distributions with $sec\theta$ shows a clear peak. Both, the position of the peak, X_{asymax}, and the size of the asymmetry at X_{asymax} are sensitive to primary mass composition and have a small dependence on energy. In this paper a study of the discriminating power of the new observables to separate primary species is presented.

1. Introduction

As it is well known, the circular symmetry observed in the signals collected by the surface detectors is broken in the case of inclined showers. Evidence of the azimuthal asymmetries in the signal size were first observed at Haverah Park [1] and the first observations of asymmetries in the time structure of the ground detector signals were found in the Pierre Auger Observatory [2]. The azimuthal dependence arises mainly due to the different paths traveled by the particles at different azimuth angles. In ground array experiments the analysis is done projecting the collected signals and time distributions at ground level into the shower plane neglecting the shower evolution. This results in an azimuth angle dependence in the slant depth, as it was proposed in [3]. The observed asymmetry in the time distributions offers a new possibility for primary composition determination, because its magnitude is strongly dependent on the muon to electromagnetic ratio at ground. We have done a preliminary study on the information in time distributions using simulations of proton and iron initiated showers with the aim of estimating the sensitivity of the Pierre Auger Observatory for hadronic primary discrimination [2]. The following observables were analyzed:"rise-time" (defined as the time between the 10% and 50% of the integrated signal) and "fall-time" (time between the 50% and 90% of the integrated signal). These variables were studied as a function of the azimuth angle in the shower plane at fixed core ranges and zenith angles, for showers initiated by proton and iron primaries.
In this paper we describe a new observable related to the asymmetry factor of the time structure of the signal in the water-Čerenkov detectors of the Pierre Auger Observatory useful to discriminate composition.

2. Asymmetries as an indication of shower evolution and mass composition

Most of the observables related to composition are like a snapshot of the shower development and then, are correlated with X_{max} and the 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 "rise-time" and "fall-time", and the corresponding asymmetries observed, with the atmospheric depth.
If we call t' the atmospheric slant depth, $t' = \int_h^\infty \rho_{atm}(z)\ dz'$ with z' along the shower axis, then, $t'(\zeta) = t\,\sec\theta\,(1 + B_0\,\tan\theta\,\cos\zeta) = t_s + \Delta t_s(\zeta)$. We can treat this dependence in a first approximation using a Taylor expansion in slant depth around $t\,\sec\theta$ keeping only the first term, considering that the azimuth angle correction is small compared to the slant depth. This is equivalent to using a linear function in cosine of the

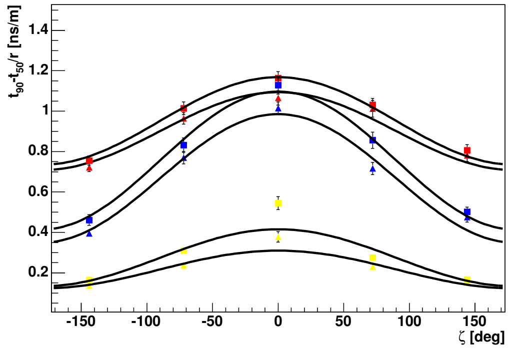

Figure 1. Fall-time as a function of ζ for 100 EeV for proton (□) and iron (▲) for 25, 45 and 60 from top to bottom.

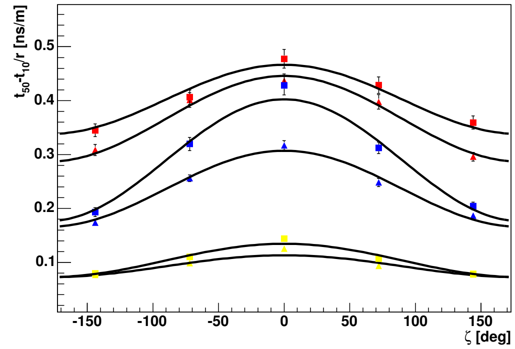

Figure 2. Rise-time as a function of ζ for 100 EeV for proton (□) and iron (▲) for 25, 45 and 60 from top to bottom

azimuth angle in the shower plane, ζ (defined with $\zeta = 0$ in the incoming direction of the shower) to describe asymmetries in data.

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 core distance perpendicular to the shower axis. For inclined showers, $\tau(r,t) \rightarrow \tau(r,t'(\zeta,\theta))$. where t' is the atmospheric depth along the shower axis and r the core distance in the shower plane. Performing a Taylor expansion around t_s, we obtain:

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

If $\tau(r,\zeta) = a + b \cos\zeta$, the asymmetry factor $\frac{b}{a}$ depends on the core distance and the atmospheric depth, and it is a measurement of the logarithmic rate of change of the variable considered.

Studying asymmetries in time distributions from this point of view allowed us to find a new observable in the dependence of the asymmetry factor with depth, useful to discriminate primary composition.

For the present Monte Carlo study, we use proton and iron initiated showers generated with AIRES 2.6.0 /QGSJET01 with primary energies 10^{19} eV and 10^{20} eV and zenith angles between 0^0 and 60^0 ($sec\theta = 1.103$, 1.221, 1.414, 1.743 and 2). The detector response of the Pierre Auger Observatory was simulated (using the official simulation and reconstruction tool, Offline v1r2) with the SDSim module in the full array configuration and with all the parameters in their default values. The resulting data were reconstructed using the reconstruction modules. The sample used consisted in 20 showers for 10^{19} eV protons, 25 showers for 10^{19} eV irons and 30 showers for 10^{20} eV proton and iron each, for each angle considered.

The dependence of the "rise-time" and "fall-time" with azimuth angle was fitted using the functional dependence, $\tau = a + bcos\zeta$. In Figures 1 and 2 we show the mean value of the timing distributions divided by core distance for proton and iron primaries as a function of ζ for the case of primary energy 10^{20}eV. The fit was performed for each primary species, energy and zenith angle, for all stations between $500m < R < 2000m$ from the core. It is important to point out that the asymmetry factor is different for different primaries, as one expects due to the greater number of muons in showers initiated by heavy nuclei than in showers initiated by protons.

We studied then the behavior of the asymmetry factor with depth represented by $\sec\theta$. The corresponding distributions show a clear peak in atmospheric depth, which is in a different position for proton and iron showers. Two examples of these distributions are presented in Figures 3 and 4, corresponding to the asymmetry factor

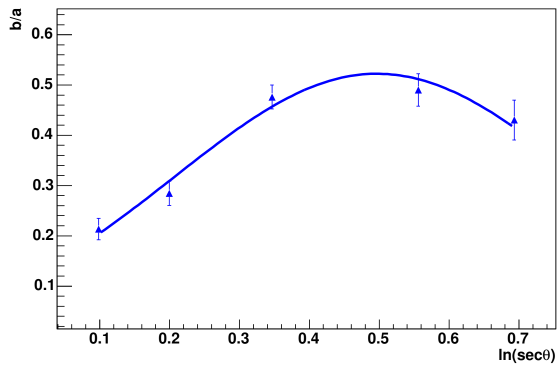

Figure 3. Asymmetry factor as a function of $\ln\sec(\theta)$ corresponding to "fall-time", for 100 EeV iron.

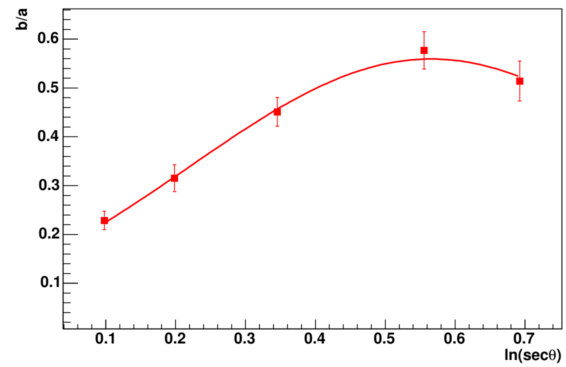

Figure 4. Asymmetry factor as a function of $\ln\sec(\theta)$ corresponding to "fall-time", for 100 EeV proton

for the "fall-time" for 10^{20} eV iron and proton respectively. The distribution is quite symmetric when plotted as a function of the logarithm of $\sec\theta$. To determine the position of this peak we fit a normal distribution in the logarithm of $\sec\theta$.

The location of the peak, $\ln(\sec\theta)_{max}$, as a function of primary energy is shown in Figure 5 for proton and iron primaries for the "fall-time". Clearly, $\ln(\sec\theta)_{max} = \ln(X_{asymax}/t)$. The error bars are the errors from the fit. The position of the peak in the dependence of the asymmetry factor with $sec\theta$ is different for different primaries and allows then to help separating primary species. The "fall-time" seems to be a better discriminating parameter than the "rise-time" at all primary energies. It is worth mentioning that the value of the asymmetry at the peak is also sensitive, although to a less extent, to the primary composition.

We also found that the difference in the peak position for proton and iron expressed in g. cm^{-2} is of the same order as the difference in X_{max} position for each energy bin. This is not surprising since observables related to composition are in some way a measurement of the stage of shower development and then, directly correlated with the shower maximum X_{max}.

3. Conclusions

Data collected by the surface detector of the Pierre Auger Observatory have proven to be extremely rich for the inference of the characteristic of the primary particle. In particular, the observed azimuth angle asymmetries in time distribution of the signals in showers with zenith angles lower than 70°, which is a unique feature of the Pierre Auger Observatory.

We focused our analysis on the study of the azimuthal asymmetry of both the "rise-time" and "fall-time" that are sensitive to the presence of the electromagnetic and muonic components of the shower and, because of this to primary composition. From a study of the dependence of the azimuthal asymmetries in these timing variables with the depth in the atmosphere using Monte Carlo simulations for proton and iron showers in different energy ranges, we have found a new observable for primary mass discrimination: A clear peak appears in the distribution of the asymmetry factor with atmospheric depth, the position of which is sensitive to primary mass. With a 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. An important feature of this study

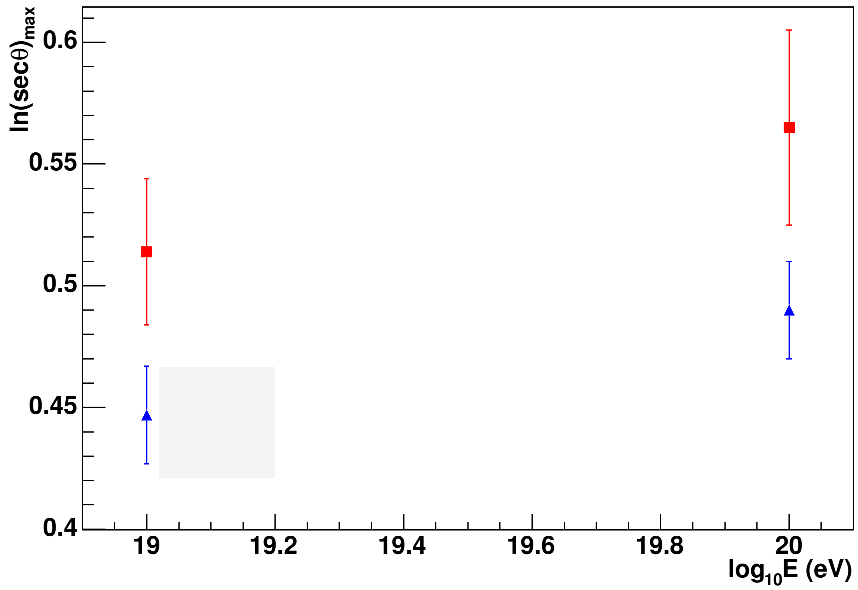

Figure 5. Maximum value of the asymmetry factor obtained from the the fit for proton (□) and iron (▲) initiated showers as a function of primary energy corresponding to "fall-time".

is the weak dependence of the new observable with energy, requiring only the knowledge of the core position with good resolution.

We have applied the method to signal pulse shape parameters but it could also be applied to some other pulse shape parameters or shower observables like the shower age.

References

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