Studies of Signal Waveforms From the Water-Cherenkov Detectors of the Pierre Auger Observatory

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The ground array of the Pierre Auger Observatory will consist of 1600 water-Cherenkov detectors. Such detectors give signals which can help differentiate between muons and electrons in extensive air showers. The relative numbers of muons and electrons is sensitive to the type of primary particle which initiated the shower. Results are presented using methods which describe the muon content and related information, such as the time structure of the shower front.

1. Introduction

The geometry and the muon content of air showers are sensitive to the type of primary particle which initiates the cascade. Nuclear primaries cause showers which develop higher and have more muons than showers started by primary protons of the same total energy. Gamma-rays produce showers with far fewer muons than hadronic primaries.

The surface detectors of the Pierre Auger Observatory use flash-ADCs (FADCs) to digitize photomultiplier signals at 40 MHz [1]. These data are used to examine the time structure of the shower front (which relates to the shower geometry) and to estimate the number of muons at the ground. A muon typically gives a larger signal than an electron or photon, because muons have relatively higher energy (GeV versus MeV) and consequently longer path lengths in the detectors.

Figures 1 and 2 exhibit FADC data from two detectors in a typical event. The signal magnitude has been normalized to that of an average vertical muon and is given in VEM units (Vertical Equivalent Muon). This shower has primary energy 12 EeV and is nearly vertical ($\theta = 6°$). Near the core (Fig.1), the signal is dominated by abundant electrons and photons. At larger distances (Fig.2), individual "spikes", very likely due to muons that pass through the tank, become apparent.
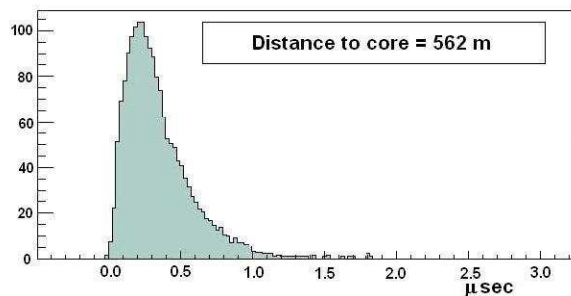

Figure 1. Sample FADC trace from a nearly vertical shower. The signal magnitude is in units of VEM (see text).
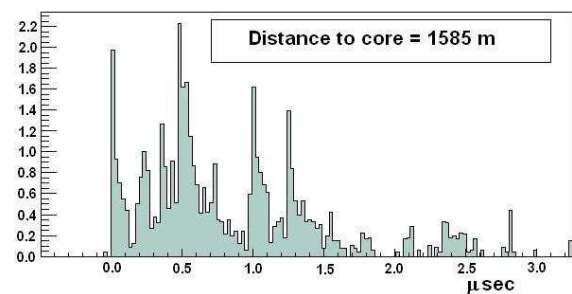

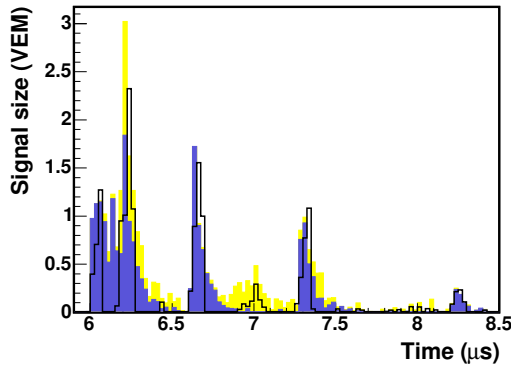**Figure 2.** As in previous figure, but at a larger core distance.

Figure 3. The signal observed in a detector station 1650 m from the core of a simulated 10 EeV iron shower at 30° zenith angle. The lightly shaded (yellow) region indicates the total signal with the more darkly shaded (blue) subset giving the signal only from muons. The result of the correlation analysis is displayed as the unshaded histogram.
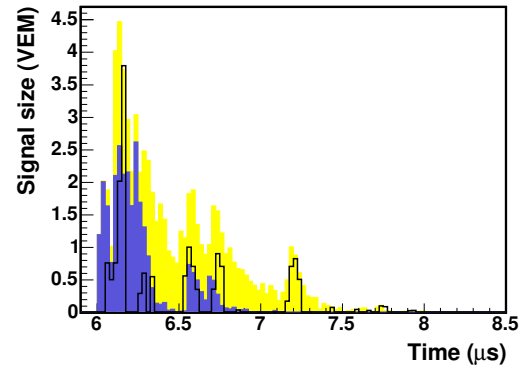
Figure 4. As in previous figure, except here for a detector station 1100 m from the core of a 10 EeV proton shower at at 30° from the zenith .

2.   Muon Counting: Pulse Shape Identification

One technique that shows promise for identifying individual muon signals is matched-filtering of the FADC traces. In this approach a normalized muon "template" signal, obtained from the single muon calibration data, is cross-correlated with the signal trace. Since the time characteristics of a single muon signal are determined by the physical characteristics of the detector station (water depth, water clarity, and wall reflectivity) and the frequency response of the front-end electronics filter, the template signal is quite stable for any given detector station. The muon-like count is obtained from the cross-correlation trace.

Care must be taken to ensure that the simulations used to evaluate the method preserve the time structure of the FADC traces. The thinning and resampling techniques normally used can distort the time structure. To minimize this effect in our study we generated a sample of very lightly thinned (thinning level 10^{-8}) proton and iron showers using AIRES with QGSJET.

Figure 3 and 4 show two simulated FADC traces. Figure 3 shows the response of a detector 1650 m from the axis of a 10 EeV iron shower at 30° zenith angle. The shaded region indicates the total signal observed in a detector station. The more darkly shaded (blue) portion indicates the signal generated by muons in the tank, and the dark unshaded histogram indicates the result of the correlation analysis. In this station there were 6 muons, which deposited an integrated signal of 6.9 Q_{VEM} (Q_{VEM} is the average total charge deposited in the FADC by vertical muons). The correlation analysis reconstructed a muon signal of 5.6 Q_{VEM} . In computing Q_{VEM} one needs to normalize the integrated muon signal by the Q_{VEM} corresponding to an average vertical muon signal, and normalize the integrated correlation signal by the area of the correlation signal for an average muon signal.

In Fig. 4 we show the corresponding set of signals for a 10 EeV proton shower with a 30° zenith angle in a station 1100 m from the shower core. Here 10 muons deposited 8.6 Q_{VEM} in the station, and the correlation analysis reconstructed a muon signal of 6.5 Q_{VEM} . Note, however, that the muon signal in this case is underestimated in the early portion of the signal, and overestimated in the late portion.
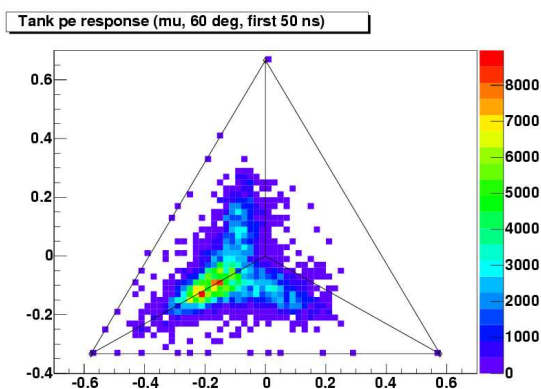
Figure 5. Ternary light deposition profile of a 1 GeV muon at 60 degrees zenith, directed towards PMT 1.
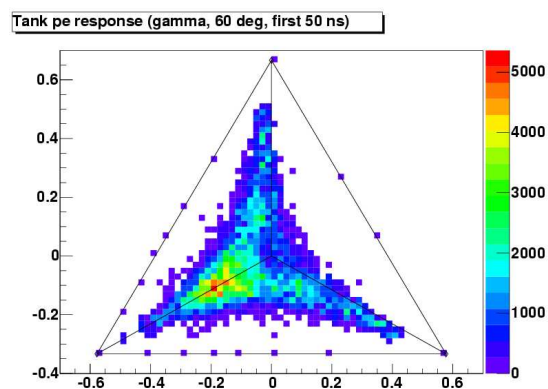
Figure 6. Ternary light deposition profile of a 100 MeV photon at 60 degrees zenith, directed towards PMT 1

Work is underway to optimize the parameters, to characterize the region of validity, and to quantify the systematic uncertainties.

3. Muon Counting: Signal Asymmetry

Determining the muon content of a shower from FADC trace analysis may be assisted using the fact that the light deposition profiles in the 3 PMTs can be an indicator of the particle incident on the tank for inclined showers. For muons, which tend to have long straight tracks, the signal will be biased towards the PMTs on the far side of the tank. For lower-energy photons and electrons (~ 5 MeV), which arrive in large numbers, spread out over distances greater than the tank, the response of the three PMTs ought to be more symmetric.

Figures 5 and 6 show *ternary light deposition profiles.* The relative fraction of light deposited into each PMT is shown on the diagram with total symmetry in the center, all light into PMT2 as the top vertex, all light into PMT3 as the bottom right vertex, and all light into PMT1 as the bottom left vertex.

Figure 5 represents a 1 GeV muon at 60 degrees zenith, directed towards PMT 1. The diagram clearly indicates the bias in signal. Unfortunately, the analysis is complicated due to the behavior of the few high-energy photons (> 100 MeV) which are typical in air showers. These can also produce asymmetric light in the PMT, as seen in Fig. 6. Thus, high energy photons can mimic muons in such an analysis. However, as seen in Fig. 6, the signal deposition from a photon is more likely to deposit charge in the PMTs on the near side of the tank, which may assist in their differentiation of these photons and proper muon counting.

4. Risetime

The *risetime* of the signal in a detector is one parameter that strongly correlates with the overall geometry of the shower. A risetime parameter $t_{1/2}$, defined as the time for the signal to increase from 10% to 50% of its full value, has been commonly adopted: it can be derived readily from the FADC traces recorded with the surface detectors of the Auger Observatory. At large distances (> 300 m) from the shower core a slow (fast) risetime indicates a shower that has developed later (earlier) than average. Risetime depends strongly on the distance
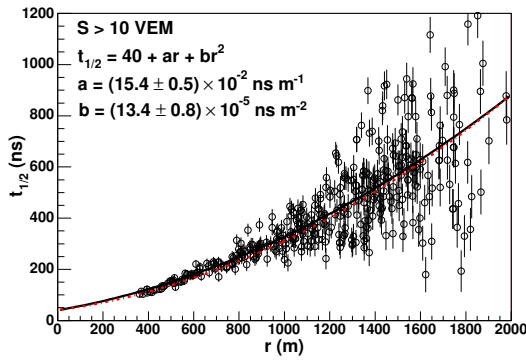
Figure 7. Rise time measurements for high energy events, from tanks with $S > 10$ VEM. Solid line is a fit, dashed line is a parameterisation from lower energy events.
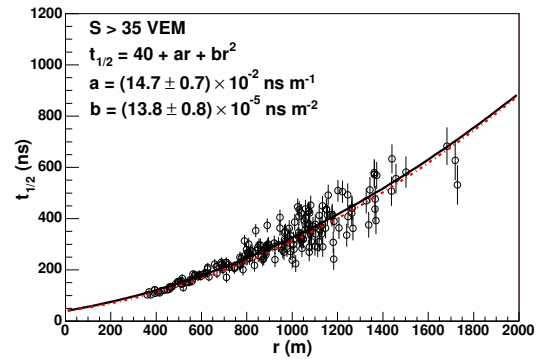
Figure 8. Rise time measurements as in Fig. 7, except for tanks with larger signals, $S > 35$ VEM.

of the detector from the shower core and on the zenith angle, but only logarithmically on the energy of the initiating primary [2][3]. In a near vertical shower, $t_{1/2}$ is found to be about 300 ns at 1 km from the shower axis as measured using the 10 m^2 water detectors of the Pierre Auger Observatory.

Figures 7 and 8 show values of $t_{1/2}$ that have been measured in a sample of events with $E > 10$ EeV and $\theta < 29°$. The two plots are for signals greater that 10 VEM and 35 VEM respectively, demonstrating the impact of Poissonian fluctuations. The solid line is a fit to these data; it is nearly identical to a parameterisation found from a much larger sample of lower energy events ($\langle E \rangle \approx 3$ EeV), shown as a dashed line (red) in the figures. The uncertainties shown are found from an analysis of data obtained from two sets of specially paired detectors (each member of a pair is separated by $\sim$11 m) and from a study of signals recorded in pairs (or triplets) of detectors that are equidistant from the shower core to within 100 m. The difference in the spread of the $t_{1/2}$ values in these two plots demonstrates the importance of fluctuations that can arise at large core distances.

There are several reasons why it is important to understand the timing characteristics of the shower front. Time parameters, such as $t_{1/2}$, can be used to divide showers into groups that have developed late in the atmosphere (presumably dominated by events initiated by nucleonic cosmic rays that are lighter than average) and early developing showers. Such a crude division has the advantage of being independent of assumptions about shower models. An example of the use of risetime in composition studies is reported in an accompanying paper[4] in which limits to the flux of photons above 10 EeV have been set. The large database of shower front parameters that will be assembled will also be used to search for events that exhibit anomalous behaviour.

References

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