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Disentangling the air shower components using scintillator and water Cherenkov detectors

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Abstract. We consider a ground array of scintillation and water Cherenkov detectors with the purpose of determining the muon content of air showers. The different response characteristics of these two types of detectors to the components of the air shower provide a way to infer their relative contributions. We use a detailed simulation to estimate the impact of parameters, such as scintillation detector size, in the determination of the size of the muon component.

1. INTRODUCTION

The measurement of the mass composition of ultra-high energy cosmic rays is one of the keys that can help us elucidate their origin. Using a surface detector array to disentangle the contributions to the detector signal from the different components of an air shower is a way to accomplish this.

Up to energies around 10^{15} eV, the Galaxy is believed to be the source of cosmic rays. Several acceleration mechanisms are certainly at play but it is widely expected that the dominant one is first order Fermi acceleration at the vicinity of supernova remnant shock waves. These Galactic accelerators should theoretically become inefficient between 10^{15} eV and 10^{18} eV. The KASCADE experiment has measured the energy spectra for different mass groups in this energy range and found that there is a steepening of the individual spectra at an energy that increases with the cosmic ray mass [1]. As a result, the mass composition becomes progressively heavy. It is also thought that extra-galactic sources can start to contribute to the total cosmic ray flux at energies above 4×10^{17} eV. The onset of such an extra-galactic component would probably produce another change in composition. The $X_{\max}$ measurements from the HiRes-MIA experiment have been interpreted as a change in composition, from heavy to light, starting at 4×10^{17} eV and becoming proton-dominated at 1.6×10^{18} eV [2, 3]. Both HiRes and the Pierre Auger Observatory has measured a suppression of the flux of cosmic rays at the highest energies [4, 5] and the $X_{\max}$ measurements hint at a light or mixed composition that becomes heavier beyond 2×10^{18} eV [6].

Roughly speaking, the techniques for inferring the mass composition of cosmic rays can be split in two categories, depending on whether they exploit the sensitivity to the depth of shower maximum ($X_{\max}$) or to the ratio of the muon and electromagnetic components of the air shower [7]. Direct measurements of the fluorescence emission fall in the first category, and so do the various measurements of the Cherenkov light produced by air showers. Most ground-based detector observables depend one way or another on the number of muons in the air shower. However, the arrival time profile of shower particles has been used as an observable mostly sensitive to $X_{\max}$, in particular the so-called *rise-time*, the time it takes for the signal to rise from 10% to 50% of the integrated signal [8]. The measurement of the number of muons and electrons in an air shower can be done directly, for example, the way it was done with the KASCADE detector [9].

It is important that we disentangle the contributions from the different components of the air shower, as this relates to the primary mass as well as possible systematic uncertainties arising from the use of Monte Carlo hadronic interaction generators.

The Pierre Auger Observatory is developing a series of enhancements that aim at measuring showers in the energy range between 10^{17} eV and 10^{19} eV [10, 11]. In particular, the objective of the AMIGA enhancement [10] is the measurement of the muon component of the air showers using scintillators shielded by several meters of soil. In the same spirit, we are considering a *combined* surface array, consisting of two super-imposed ground arrays, a Water Cherenkov Detector (WCD) array and a scintillation detector array. The purpose of the scintillation detectors is to increase the sensitivity to the electromagnetic component of air showers.

In this article we consider the possibility of studying extensive air showers induced by cosmic rays using a combined detector consisting of water Cherenkov and scintillation detectors. In order to do this, we have developed a detailed simulation and reconstruction chain whose characteristics will be briefly described in Section 2. We will then look at the general features that allow us to gain sensitivity to the mass composition of cosmic ray primaries at energies around 10^{18} eV and conclude, in Section 4, by considering the possibility of determining the contribution from the muon component of a shower from a pair of scintillation and WCD detectors.

2. STUDYING THE CHARACTERISTICS OF A COMBINED SURFACE DETECTOR

The detector setup we are considering consists of an array of WCDs and an array of scintillators, both covering the same area. Each WCD is like a typical Pierre Auger detector. That is: it is made of a 12 ton cylindrical water tank with $10\,\mathrm{m}^2$ top surface area and the light is collected by three 9 inch photomultipliers placed at the top of the tank facing down. The light collected on the PMTs is then digitized by a 40 MHz Flash ADC.

The array of scintillation detector stations is arranged in a regular grid. We have considered different grid configurations and these will be specified in Sections 3 and 4. Each scintillation detector station is made of 3 cm thick plastic scintillator tiles. In order to enhance the signal from gamma-rays in air showers, we have studied the effect of adding a certain amount of lead on top of the scintillators. For conversion of around 80% of the high energy gamma-rays one normally needs a shielding of about 2 radiation lengths. One radiation length corresponds to 0.56 cm of lead.

In order to study such a combined detector, we have implemented a simulation and reconstruction chain based on the Pierre Auger Observatory offline framework [12]. All showers were generated using CORSIKA [13], with QGSJET II for high energy hadronic interaction simulations [14]. The specific zenith angles and energies studied will be mentioned in Sections 3 and 4. The simulation of the interactions of the shower particles with the detector is done using the Geant4 package [15, 16]. The scintillation efficiencies used in the simulation correspond to the specifications for Bicron's BD-416 scintillators: Polyvinyl Toluene scintillators with a nominal light yield of about 10^4 photons/MeV and a density of $1.032\,\mathrm{g/cm}^3$. The resulting scintillation photons are sampled with a 100% efficiency at a frequency of 100 MHz to produce one FADC trace per station. The signal in each station is measured in units of *Minimum Ionizing Particle* equivalent, or *MIP*, where a MIP is given by the position of the peak of the Landau distribution for vertical muons. We then consider only stations with signals between 1 and 2000 MIP in order to simulate a limited dynamical range.

The arrival direction and core position of each event are estimated using only the WCDs. The arrival direction is determined by fitting a spherical shower front to the signal start times of the stations in the event. The core position is determined by adjusting a lateral distribution function (LDF) of the form

$$\left(\frac{r}{S_{r_0}}\right)^{\beta}\left(\frac{r+700\mathrm{m}}{S_{r_0}+700\mathrm{m}}\right)^{\beta+\gamma} \tag{1}$$

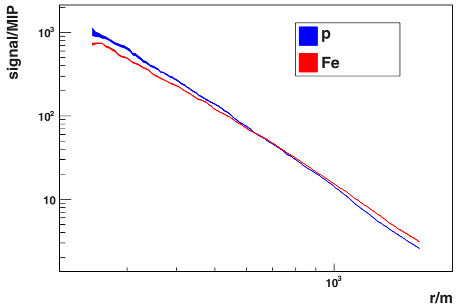


Figure 1. p-Fe LDF Comparison at 38° (E = 10^{18} eV). The lines correspond to the average over 400 showers.

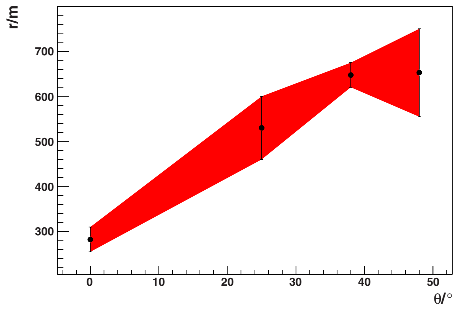


Figure 2. p-Fe LDF Crossing Points ($\theta = 38°$, E = 10^{18} eV).

to the total signal in the stations in the event. The r_0 parameter depends on the WCD array grid spacing. It will be 450 m when the stations are separated by 750 m and 1000 m when they are separated by 1500 m. Correspondingly, S_{450} and S_{1000} are the usual energy estimators for a WCD array with these grid spacings as they are close to the optimum distance for determining the signal in each case [17, 18].

3. MEASURING COMPOSITION AT ENERGIES AROUND 10^{18} EV

We have considered various configurations in order to estimate the cosmic ray primary composition at energies around 10^{18} eV. In a previous contribution we showed that the addition of lead converters on top of the scintillator stations to enhance the contribution from photons in the shower does not increase the sensitivity to the primary mass [19]. We have also considered various spacings between scintillator detectors, while keeping the total array area as well as the total collecting area constant. We have considered three such arrangements for the scintillator array, corresponding to three different spacings: 433, 612, and 750 m regular triangular grid. The area of the scintillator stations in these configurations are 3.2, 6.4, and 9.7 m^2 respectively.

One can see in Figure 1 that the average LDF from light primaries is steeper than that from heavier primaries. In order to be sensitive to the mass of the primary, one needs to sample the LDF at points away from the crossing point of the two LDFs. This crossing point depends on energy as well as zenith angle, as displayed in Figure 2. We need therefore to measure the signal either close to or far away from the shower axis. Since we are considering this scintillator array to be placed around a base configuration consisting of a fixed-size WCD array, it follows that the scintillators must probe the region close to the axis.

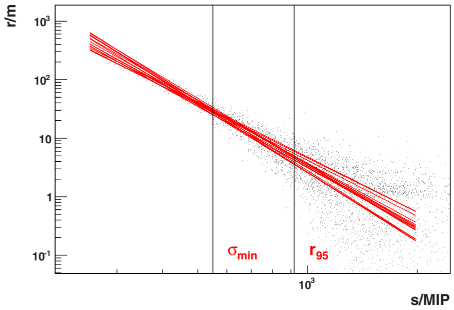


Figure 3. A set of reconstructed scintillator LDFs (proton, $\theta = 38^{\circ}$, E $= 10^{18}$ eV).

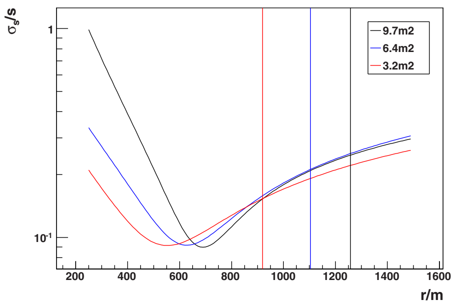


Figure 4. Relative signal fluctuations for the different array configurations considered. Same parameters as in Fig. 3.

The signals from the scintillation detectors are used to estimate an LDF on an event-by-event basis using a function of the form

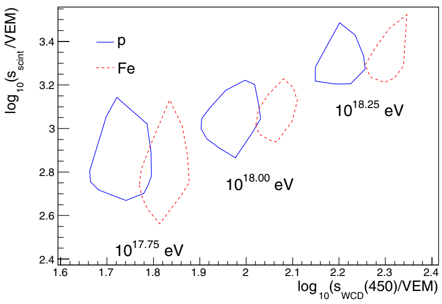
$$S_{\rm sci}(r) = S_{r_0}\left(\frac{r}{r_0}\right)^{-\beta}. \tag{2}$$

A sample of a few reconstructed LDFs is depicted in Figure 3. In this figure one can see that there will be an optimum distance from the shower axis to measure the scintillator signal. The optimum radial distance will be the one where the spread of the reconstructed signal relative to the total reconstructed signal is minimal. This is shown in Figure 4, where we display the relative signal fluctuations for the different configurations used. For reference, in both figures, we display the radius at which the local trigger is 95% efficient, r_{95}. At this point it becomes clear that trading off individual detector size for a denser array will increase the composition sensitivity, since the optimum distance will be displaced closer to the axis.

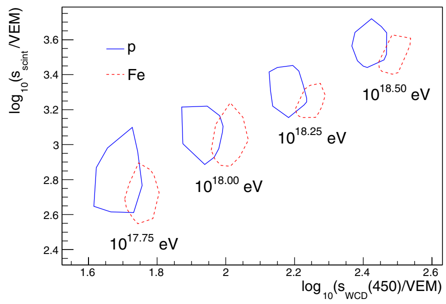
In a similar way, the optimum distance for composition sensitivity is found by minimizing the signal fluctuations in relation to the average separation of the proton and iron LDFs. For this reason one can choose slightly smaller distances to the shower axis. We can then correlate the recorded scintillator signal at a specified distance with the WCD at 450 m. This correlation, with the scintillator signal measured at 400 m, can be seen in Figure 5. From the $\log_{10}(S_{\rm sci})$ $\log_{10}(S_{\rm WCD})$ correlation it is possible to provide an estimator of the primary mass composition.

4. ESTIMATING THE MUON SIGNAL AT THE HIGHEST ENERGIES

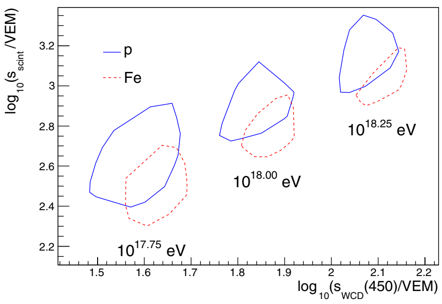
In the previous Section we discussed how to use an array of scintillators to measure the electromagnetic (EM) component of air showers and found that decreasing the spacing between the scintillators increases



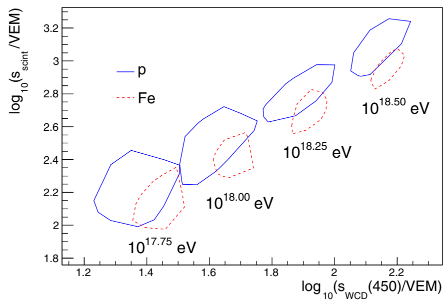
(a) θ=0°



(c) θ=25°



(b) θ=28°



(d) θ=48°

Figure 5. 68% Contours of the $\log_{10}(S_{\mathrm{sci\,400m}})$ $\log_{10}(S_{\mathrm{WCD}})$.

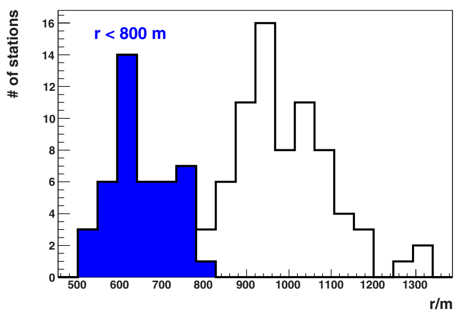


Figure 6. Closest Station Distribution for $10^{19.5}$ eV proton showers arriving at 38. See text for details.

the sensitivity to the primary mass composition. The LDF of the electromagnetic component is steeper, therefore we need a denser array in order to reconstruct it.

We now turn to the other extreme. We will consider how well we can determine the contributions from the EM and muon components in a single pair of WCD/scintillator stations, one next to the other. At the highest energies, the electromagnetic LDF will extend to larger distances and, while it will then not be possible to reconstruct it using an array of scintillators separated the same distance as the WCD detectors, a significant fraction of events will contain at least a pair of WCD/scintillator stations with which to determine the contribution from the EM and muon components.

We are then interested in the fraction of events that will have a station with a signal at a short distance to the axis. In Figure 6 we show the radial distribution of the non-saturated station closest to the axis for

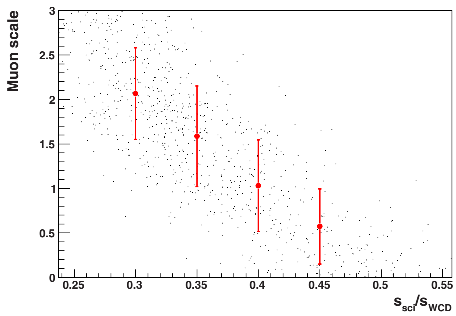


Figure 7. Correlation between an artificial scaling of the muons in the shower and the ratio of the scintillator and WCD signals for the closest station.

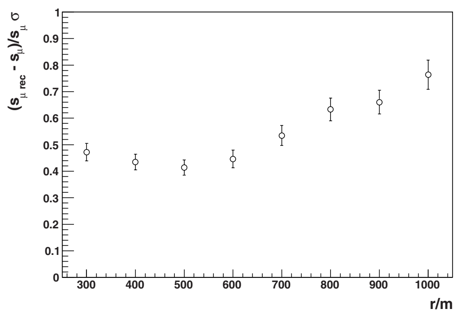


Figure 8. Statistical uncertainty on s_μ.

each event in a collection of $10^{19.5}$ eV protons arriving at a zenith angle of 38°. One can see that 30% of the events will have at least one station within 800 m of the axis (the region marked in blue). The peak around 1000 m corresponds to events where the closest station is saturated. The radial distribution shows two distinct peaks. The peak around 950 m corresponds to events where the WCD station closest to the axis is saturated and therefore the station that enters the distribution is the closest WCD station that is not saturated. If we consider the closest WCD station, regardless of its saturated status, the fraction raises to 95%.

The relation between the scintillator and WCD signals should provide, in principle, a way to estimate the contribution from the muon component, as shown in Figure 7, where we depict a collection of $10^{19.5}$ eV protons arriving at 38° with the vertical where we have scaled the number of muons by an arbitrary factor between 0 and 3. We use the linear correlation between the scintillator and WCD signals for each component:

$$s_{EM}^{\mathrm{sci}} = \alpha_{EM} s_{EM}^{\mathrm{WCD}} \tag{3}$$

$$s_\mu^{\mathrm{sci}} = \alpha_\mu s_\mu^{\mathrm{WCD}} \tag{4}$$

to determine s_μ^{WCD}, the contribution from the muon component to the WCD signal.

In Figure 8 we show the statistical uncertainty with which we can measure s_μ^{WCD} when we use scintillator stations with an area of 1.6 m^2. This uncertainty is between 40% and 50% and could be reduced by increasing the detector size. For 10 m^2 detectors it would be around 30%. This calculation was done for stations at fixed radii but the uncertainty in the core position introduces another source of uncertainty that is related to slight changes in α_{EM} in equation 3. The impact of this effect can be

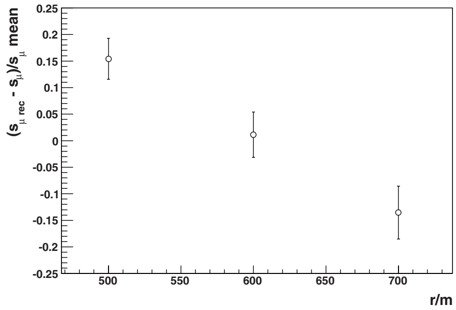


Figure 9. Systematic deviations on s_μ arising from an incorrect distance to the core.

estimated and is shown in Figure 9. From this we can conclude that an uncertainty of 30 m in the core position would produce an uncertainty of less than 5% in the reconstructed muon signal.

5. SUMMARY

We have conducted a detailed study of the sensitivity of a combined scintillator/WCD array to primary cosmic-ray mass composition. Studying the response of this array to 10^{18} eV showers, we have concluded that adding photon converters on top of the scintillators to enhance the signal from the electromagnetic component of the shower does not increase the sensitivity. We have also concluded that having many small scintillation detectors is better than having few detectors of larger size since the optimum distance is closer to the shower axis. Specifically, an array of 3.2 m^2 detectors separated by 375 m is better than an array of 9.7 m^2 separated by 750 m.

We have applied these ideas to the highest energies and determined that, for $10^{19.5}$ eV primaries, more than 30% of the events will have a pair of scintillator/WCD station within 800 m of the axis. Using this pair stations it would be possible to estimate the signal from the muon component in the WCD tanks with an uncertainty of 50% when the WCD station has an area of 10 m^2 and the scintillator has an area of 1.6 m^2. This uncertainty can be reduced by increasing the scintillator size.

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