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A generalized description of the time dependent signals in extensive air shower detectors and its applications

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ABSTRACT

The expected signal in extensive air shower (EAS) detectors can be predicted with a 10% accuracy by a parameterization that depends on a set of global shower parameters: the energy, the depth of the electromagnetic shower maximum (X_{max}) and the overall muon content. By classifying shower particles in four components (muonic, purely electromagnetic, electromagnetic stemming from muon interactions and decay and electromagnetic-from-low-energy hadrons), shower-to-shower fluctuations are minimized. We follow this scheme to propose a model to describe the arrival time distributions of secondary particles as measured with surface detectors in an EAS experiment. This model is then used to reconstruct X_{max} in Monte Carlo data sets. As an example, we show that for the case of the Pierre Auger Observatory X_{max} can be reconstructed with an accuracy of about 45 g/cm^2 at 10^{19} eV.

1. Introduction

The origin of ultra-high energy cosmic rays (UHECR, with energies beyond 10^{18} eV) still remains a mystery. Experimental results [1–4] suggest that the UHECR flux is composed predominantly of hadronic primary particles. As charged particles they suffer deflections in cosmic magnetic fields which smear small-scale angular anisotropies and difficult the identification of the sources. An indirect search for their origin is necessary instead: the precise measurement of the energy spectrum, an estimation of the mass composition and its evolution with energy, and large-scale angular anisotropies are the three main handles on disentangling this almost century-old problem.

Due to the low fluxes at ultra-high energies the detection of UHECR can only be achieved by measuring extensive air showers (EAS), cascades of secondary particles resulting from the interaction of the primary cosmic rays with the atmosphere. The measurement of the cosmic ray energy and mass relies on a good understanding of this phenomenon.

The depth of the electromagnetic shower maximum (X_{max}) is sensitive to the mass composition of the primaries. It can be measured directly in EAS experiments with fluorescence detectors. The aim of this work is to prove that such measurement is also possible with an array of surface detectors. X_{max} estimation using surface detector arrays is interesting for two reasons: (a) it can potentially increase the available statistics for composition studies in current experiments by a significant amount; (b) if X_{max} resolutions are in the 30–40 g/cm^2 range, anisotropy studies for a small subset of *light* events can bring insights on the origin of UHECRs.

The underlying idea of this work is that there is a one-to-one mapping of the shower particle time distributions at any known stage of shower development and the overall longitudinal development. This idea has been used in the past to infer the longitudinal development of the muonic component by using the arrival time of single muons detected in surface detectors [5]. In this work, we extend this idea to the electromagnetic component. The diffusive propagation of electrons and gamma-rays, together with the lack of individual particle classification capabilities in current EAS detectors have forced us to develop a statistical instead of a per particle technique: the overall time distributions are modelled depending on the stage of shower development. The drawback of this procedure is that only the depth of the shower maximum (instead of the whole longitudinal development) can be inferred.

The electromagnetic component of extensive air showers of very high energy is characterized by a number of important features, see for example [6–9]: the energy spectrum and angular distribution of electrons and gamma-rays depend mainly on the stage of the shower development and the distance to the shower axis regardless the incoming primary. To exploit these properties in the analysis of data of modern cosmic ray detectors it was necessary to extend the concept to the muonic shower component. Using simulations it was found that the longitudinal development of muons in

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an air shower has a common shape for a wide variety of hadronic models and primaries, with only the normalization and depth of the shower maximum changing from shower-to-shower. Based on this finding, a parameterization of the signal expected in surface detector stations such as the Pierre Auger Observatory had been developed for a distance of 1000 m from the shower core [10].

In [11], a new description of the ground signals in air showers was presented. It was found that a substantial part of the electromagnetic component at large core distances is due to sub-showers with large transverse momentum initiated by neutral pions produced in hadronic interactions at low energy. A new shower component was introduced to account for this effect.

This scheme was then used in [12] to develop a model for the time distribution of shower particles convolved with the detector response. This model together with [11] was then used to show that $X_{\max}$ can be inferred from surface detector information alone.

In this work, we propose a new model for the time distribution along the same ideas presented in [12]. We validate it with two types of detector and study the systematic uncertainties due to different choices of hadronic models and primaries. We also propose a simplified version of the $X_{\max}$ reconstruction presented in [12] and a scheme to calibrate the residual hadronic model/primary dependences of the model with real data.

2. Air shower simulations and shower components

We used Geant4 [13] to simulate two types of detector: the Pierre Auger water-Cherenkov detectors and scintillation detectors above ground, see [11] for further details.

Full Geant4 simulations of the detector response are performed in a grid of incident particle type, energy and direction. The resulting photoelectron probability distributions are stored. The response is then calculated through an interpolation of those distributions.[1]

The shower library used in this work was simulated with CORSIKA [14]. Proton/iron QGSJetII03 [15] and proton/iron EPOS1.99 [16] are simulated in a grid of zenith angle, θ, and energy, E. The following zenith angles are considered: 0°, 12°, 25°, 36°, 45°, 53° and 60°. The simulated energies are $10^{18.6}$ eV, 10^{19} eV, $10^{19.5}$ eV and 10^{20} eV. More details on the library can be found in [11].

The signal in a detector released by a shower is calculated using the resampling procedure described in [17] and the Geant4 probability distributions. For each CORSIKA entry, the average number of particles that would enter in a detector is calculated. This information is used to build two time-dependent signals: (a) *average* traces: using the average number of particles and sampling the Geant4 probability distributions, (b) *resampled* traces: using a randomly selected number of particles from a Poisson distribution with mean equal to the average, and sampling the Geant4 probability distributions. The photoelectrons are spread in time according to the photoelectron time distribution of vertical muons. In the case of muons, the parameterized decay probability is used to calculate the contribution of the Michel electron. The *average* traces are what would be measured if the same shower was recorded many times and the average was taken. The *resampled* traces would be the result of one measurement. *Average* traces are used for model building. *Resampled traces* are used when the proposed EAS reconstruction procedures are tested with Monte Carlo (MC). The time-dependent signals are stored in bins of 2, 12.5 and 25 ns.

The shower plane is the plane perpendicular to the shower axis that contains the point at ground for which the signal is evaluated. The Ψ angle is the azimuthal angle of this point in the shower plane ($\Psi = 0°/180°$ corresponds to upstream/downstream). We use a Cartesian coordinate system with the xy axis in the shower plane and the z axis pointing upward. The distance to the shower core r is calculated in the xy plane.

The sampling areas used to calculate the detector signals are slices of rings in the shower coordinate system, see [11] for more details.

The stage of shower development is quantified by the variable ΔL : the distance (in 10 m units) along the shower axis between the height at the projected detector position and the height of the electromagnetic shower maximum $X_{\max}$.

Time dependent signals will be parameterized separately for the four shower components in [11]: (a) the muonic component, (b) the electromagnetic component stemming from muon interactions and muon decay, (c) the purely electromagnetic component, and (d) the electromagnetic component from low-energy hadrons (jet component). The component d (*jets*) introduced in [11] refers to electromagnetic particles for which the spatial distribution at ground is determined by the momentum of the mother particle at the last hadronic interaction.

In this work, the overall muon content in a shower will be characterized by N_μ: the ratio of the muonic signal to the predicted value for a proton QGSJetII-03 shower with the same energy and $X_{\max}$. It is evaluated at r=1000 m and $\Psi = 90°$.

3. Time model

The time-dependent signal in a surface detector can be described by

$$\frac{\mathrm{d}S}{\mathrm{d}t}(t) = \int G(t-t')\frac{\mathrm{d}P}{\mathrm{d}t}(t)\mathrm{d}t', \tag{1}$$

where G is the time response of a detector to an instantaneous pulse, $\frac{\mathrm{d}P}{\mathrm{d}t}$ is the arrival time distribution of particles weighted with the detector response,[2] and t is the time referred to a planar front travelling at the speed of light.

Our aim is to use the time model in reconstructing EAS. This requires a semi-analytic model fast enough to be used in likelihood minimizations. Since convolution is a time consuming process, we adopt an analytic ansatz for the convoluted response. Our choice is a log-normal distribution:

$$\frac{\mathrm{d}S}{\mathrm{d}t}(t) = \frac{1}{\sqrt{2\pi}(t-t_0)s}\exp - \frac{(\ln(t-t_0)-m)^2}{2s^2}, \tag{2}$$

where t_0 is a time below which no particles are expected.[3]

For small core distances the width of the $\frac{\mathrm{d}S}{\mathrm{d}t}$ distribution is mainly due to $G(t)$. In this regime only the start time of the signal contains physical information. The left panel in Fig. 1 shows $G(t)$ for a water-Cherenkov detector from Geant4 simulations together with the log-normal ansatz (using the same fitting procedure that is described below). Even if $\frac{\mathrm{d}P}{\mathrm{d}t}$ is a delta function, the start time of the signal can be well characterized by the ansatz.

The time model will be constructed using a reference interaction model and primary, proton QGSJetII-03. First, an origin of times will be parameterized as a function of ($X_{\max}$, θ, E), and used to compute t_0 for each sampling area. Then, the optimum values of (m, s) in Eq. (2) will be derived using the time quantiles on a *per shower* basis. The values of (m, s) will then be parameterized as a function of (r, ΔL, $\Psi|\theta$, E). This procedure is done for each of the shower components and detector responses considered. The 2 ns *average* traces are used.

[1] In the case of muons, we tabulate the decay probability, the signal released by non-decaying muons, the signal of a muon before it decays and the signal due to its Michel electron. A time delay between the last two signals is introduced to account for the muon lifetime.

[2] Including time differences between energy depositions, e.g. muon decay.

[3] This ansatz was first introduced in [12] within the same context.