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Reconstruction of air shower muon densities using segmented counters with time resolution

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ABSTRACT

Despite the significant experimental effort made in the last decades, the origin of the ultra-high energy cosmic rays is still largely unknown. Key astrophysical information to identify where these energetic particles come from is provided by their chemical composition. It is well known that a very sensitive tracer of the primary particle type is the muon content of the showers generated by the interaction of the cosmic rays with air molecules. We introduce a likelihood function to reconstruct particle densities using segmented detectors with time resolution. As an example of this general method, we fit the muon distribution at ground level using an array of counters like AMIGA, one of the Pierre Auger Observatory detectors. For this particular case we compare the reconstruction performance against a previous method. With the new technique, more events can be reconstructed than before. In addition the statistical uncertainty of the measured number of muons is reduced, allowing for a better discrimination of the cosmic ray primary mass.

1. Introduction

Although the origin of the ultra-high energy cosmic rays is still unknown, significant progress has been recently achieved from data collected by setups like the Pierre Auger Observatory [1] and the Telescope Array [2]. The three main observables used to study the nature of cosmic rays are their energy spectrum, arrival directions, and chemical composition. Certainly, composition is a crucial ingredient to understand the origin of these very energetic particles [3], to find the spectral region where the transition between the galactic and extragalactic cosmic rays takes place [4], and to elucidate the origin of the flux suppression at the highest energies [5].

For energies larger than 10^{15} eV, cosmic rays are studied by observing the atmospheric showers produced when they interact with the air molecules. Therefore composition has to be inferred indirectly from parameters measured in air shower observations. The observables most sensitive to the primary mass are the depth of the shower maximum and the number of muons generated during the cascade process. While the maximum depth is observed with fluorescence telescopes, the muons are measured at ground level and underground with surface and buried detectors respectively. Besides composition, hadronic interactions can also be studied with muons. At the highest cosmic ray energies the hadronic interactions are unknown, so models that extrapolate accelerator data at lower centre-of-mass energy are used in shower simulations. As the number of muons predicted by simulations strongly depends on the assumed interaction model, the muon data can be used to discriminate among different scenarios [6–10].

In Auger, using the water-Cherenkov detectors of its surface array, muons have been measured by disentangling them from other shower particles. However this technique can only be applied when muons produce a large fraction of the total signal. Those special cases include inclined showers with zenith angle between 62° and 80° [8], and also showers close to 60°. However, in this second case, only detectors more than 1000 m away from the shower core are used [7]. To include the more abundant vertical showers and to extend the reach to lower energies, dedicated muon counters are called for. Currently Auger is building a triangular array of muon counters spaced every 750 m as part of the AMIGA project [11]. Once finished the AMIGA array will cover 23.5 km^2 in a small region of the surface detector. The detector is designed to measure showers between 3×10^{17} eV and 10^{19} eV, the upper limit determined by the number of events that can be collected given the detector size. Each grid location will have three 10 m^2 counters made out of plastic scintillator, buried 2.5 m underground, and divided into 64 scintillator strips of equal size. The three counters installed at each array site are equivalent to a

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single 30 m^2 detector divided into 192 bars. Muons are counted in time windows of 25 ns, the duration corresponding to the detector dead time given by the width of the muon pulse.

Close to the shower core the muons are accompanied by energetic electrons and gammas. However the soil shielding significantly reduces the contamination of the detector signals by these electromagnetic particles. The soil density at the AMIGA site, 2.4 g cm^{-3}, entails a shielding of 22 radiation lengths at 2.5 m underground. Using these parameters, shower simulations including the propagation of particles underground show that the electromagnetic contamination is negligible in AMIGA but very close to the shower core [12].

AMIGA measures the fall of the muon density with the distance to the shower axis, i.e. the so-called *lateral distribution function* (LDF). The LDF evaluation at a reference distance is a long-established method to characterise the size of an air shower [13]. In the surface arrays of the cosmic ray observatories, the LDF is fitted to the detector data by either minimising a χ^2 or by maximising a likelihood function [14,15]. The used likelihood, modelling the detector response to incoming particles, is specific to each detector type. In this paper we present a likelihood suitable for a particular detector, namely a segmented particle counter with time resolution like that used in AMIGA.

We fit the LDF to the detector data by maximising a likelihood that links a muon density to the observed signals. We previously used two likelihood models. In the first method we adopted an approximation valid for few muons in a detector [16]. Using this approach we showed in [17] that detectors saturate if there are more than 174 muons in a time window. As consequence events with a core falling less than 100 m from a detector cannot be reconstructed. To enlarge the statistics we later proposed another likelihood model valid for higher signals, thus covering an interval where the detector response departs from linearity. In this second case, to obtain an analytic expression, the time resolution of the detector had to be neglected. This method just considered whether a scintillator bar has a signal during the whole duration of the event.

Although the second likelihood improved the original one, grouping muons into a single time window is a drawback since shower particles arrive at the ground spread in time. For both the electromagnetic and muonic shower components, the Kascade-Grande array has measured signal widths of 70 ns beyond 400 m from the core [18]. At larger core distances, common in larger observatories, the particles arrive even more widespread and, consequently, the air shower signals extend over many 25 ns time windows. To make the best use of the detector capabilities, we improved the likelihood by including the signal timing. We started by considering the complete likelihood of a segmented detector with time resolution. To get rid of nuisance parameters present in the full likelihood, we applied two different approximations: the profile [19] and the integrated likelihoods [20]. The first technique, well established in the field of high-energy physics, was used in the discovery of the Higgs boson [21].

The following section describes the profile and the integrated likelihoods, and Section 3 illustrates them with examples. Section 4 presents the simulations used to evaluate the likelihoods. We compare the performance of the new and old methods in Section 5, and conclude in Section 6.

2. Likelihood of a segmented detector

2.1. Likelihood of a single time bin

We built the profile and integrated likelihoods as extensions of the single-window likelihood developed in [17]. For completeness some of the material developed in that work is summarised below. We must recall that the main goal of the counters used in a cosmic ray observatory is to estimate a particle density (ρ). The density multiplied by the detector area (a) and the zenith angle cosine of the shower direction is the average number of particles expected in the counter (μ),

$$\mu = \rho\, a \cos\theta. \quad (1)$$

In turn, μ is the parameter of a Poisson distribution that describes the actual number of particles impinging on the detector. Correspondingly, for a detector divided into n parts, the number of muons in each segment fluctuates according to a Poissonian with parameter μ/n.

The arriving particles produce a signal in some of the detector segments. Occasionally two or more muons pile up in the same segment. Depending on the number of particles, each segment can take two distinct states: *on* if hit by one or more muons, and *off* otherwise. According to Poisson, the probability of a segment *off* is $q = e^{-\mu/n}$, and the odds of an *on* state is $p = 1 - q$. Since the segment states are independent from each other, the probability of k segments *on* out of a total of n segments follows the binomial distribution,

$$P(k;\mu) = L(\mu;k) = \binom{n}{k} p^k q^{n-k} = \binom{n}{k} e^{-\mu}\left(e^{\mu/n} - 1\right)^k. \quad (2)$$

In addition to a probability, Eq. (2) is the likelihood of μ expected muons when k strips out of n are *on*. If $k < n$, the corresponding maximum likelihood estimator ($\hat{\mu}$) is,

$$\hat{\mu} = -n \ln\left(1 - \frac{k}{n}\right). \quad (3)$$

If $k = n$ the likelihood tends to unity when μ increases, and the maximum likelihood estimator of μ tends to infinity. In this case, the likelihood sets a lower bound to the number of muons allowed in the LDF fit [17]. Based on this behaviour we labelled these detectors as *saturated*.

The proposed likelihood only considers the detector size and segmentation. This function excludes any signal contamination produced either in the detector electronics or in the photomultipliers. This simplified model of the likelihood is realistic because the AMIGA detector filters out the detector noise. The electronic noise is filtered by tuning the discrimination level applied to the analogue signals produced by the photomultipliers. In turn any casual photomultiplier after pulse is removed by requiring the digital signals to be compatible with at least two photoelectrons [22].

2.2. Profile likelihood

To extend the likelihood to many time bins, one has to consider the time spread of the muon signal $d\mu(t)/dt$. The number of expected muons (μ) is the integral of this signal over the event duration, $\mu = \int \frac{d\mu(t)}{dt}\, dt$. Correspondingly, within a time bin, the number of muons (μ_i) is the integral restricted to the window limits. The sum of the μ_i's is μ.

The AMIGA segmented detector counts particles in windows of 25 ns. For each of these time bins, the number of strips *on* (k_i) is computed. Considering that the k_i's of different time windows are independent from each other, the likelihood of μ_i particles in the ith bin is given by Eq. (2). The likelihood of all time bins ($L(\boldsymbol{\mu})$) is the product of the single-window likelihoods,

$$L(\boldsymbol{\mu}) = \prod_{i=1} L_i(\mu_i), \quad (4)$$

where i runs over the time bins and $\boldsymbol{\mu} = (\mu_1, \mu_2, \ldots)$.

In the LDF fit, the parameter of interest is the total number of muons μ. However the value of μ alone is not enough to calculate the likelihood because this function also depends on each of