Astroparticle Physics 87 (2017) 23–39

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

A generalized description of the signal size in extensive air shower detectors and its applications

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ARTICLE INFO

Article history:
Received 26 August 2016
Revised 4 November 2016
Accepted 29 November 2016
Available online 30 November 2016

Keywords:
Air shower simulation
UHECR
Mass composition

ABSTRACT

The number as well as the energy and angular distributions of particles in extensive air showers (EAS) depend on the stage of the shower development and the distance to the shower axis. In this work we derive an analytic parameterization of the particle distributions at ground from air shower simulations convolved with the response of a surface detector array. Shower particles are classified into four components according to the shower component they belong to: the muonic component, the electromagnetic component stemming from muon interactions and muon decay, the purely electromagnetic component, and the newly introduced electromagnetic component from low-energy hadrons. Using this scheme, we will show that the total signal at ground level for different surface detectors can be described with minimal fluctuations with parameterizations depending on the primary energy, position of the shower maximum, and the overall number of muons in the shower. The simulation results for different combinations of primaries and hadronic interaction models are reproduced with an accuracy better than 5–10% in the range from 100 m to 2000 m from the shower core. This parameterization is then used as a Lateral Distribution ansatz to reconstruct showers in current EAS experiments. Since this ansatz depends on physical parameters, it opens the possibility to infer them from data.

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 and do not point back directly to their sources. Instead, an indirect search for their origin is necessary: the precise measurement of the energy spectrum, an estimation of the mass composition and its evolution with energy, and anisotropies in the arrival directions are the three main handles on disentangling this century-old problem.

Due to the low flux at ultra-high energies, the detection of UHECRs 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 Earth's atmosphere. The measurements of the cosmic ray energy and mass rely on a good understanding of this phenomenon.

The electromagnetic component of extensive air showers of very high energy is characterized by a number of important features, see for example [5–8]: the energy spectrum and angular distribution of electrons and gamma rays depend mainly on the shower age and the distance to the shower axis regardless of the primary particle. To exploit these properties in the analysis of data of modern cosmic ray detectors, it is necessary to extend the concept to the muonic shower component. Using simulations it was found that the longitudinal profile of muons in an air shower has a common shape for a wide variety of hadronic models and primaries (significant differences were only found in the normalization and depth of the shower maximum). Based on this finding, a parameterization of the expected signal in surface detector stations, such as the ones employed at the Pierre Auger Observatory, had been developed for a distance of 1000 m from the shower core [9].

In this paper, we explain a new description of air showers. In contrast to the previous parameterization, we introduce a new shower component which accounts for sub-showers of large transverse momentum initiated by neutral pions produced in hadronic interactions at low energy. This new component exhibits a natural scaling with the muon production in the shower: the neutral pions are produced together with charged pions that decay into muons. We explicitly use this relationship.

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http://dx.doi.org/10.1016/j.astropartphys.2016.11.008

2. Air shower simulations

2.1. Detector simulations

We used Geant4 [10] to simulate three types of detectors to be exemplary for modern UHECR experiments: the Pierre Auger water-Cherenkov detectors (WCD) and scintillation detectors above as well as below ground.

The water-Cherenkov detectors are described in [11]. The surface scintillators are comprised of 27 strips of plastic scintillator (1 cm thick, 4 cm wide, and 180 cm long; total area: 1.94 m^2) placed on top of the water-Cherenkov detectors. The strips are complemented with an optical fiber that collects and guides scintillation photons. The number of photoelectrons in the connected PMT depends on the energy deposit and the position of the hit. The detector is similar to the AMIGA setup [12], but placed above ground. This is a configuration similar to the envisaged upgrade of the Pierre Auger Observatory [13].

Full Geant4 simulations of the detector response are performed in a grid of incident particle type, energy, and direction. The resulting photoelectron distributions are tabulated. The response is then calculated through an interpolation of the distributions. The signal unit in these two types of detectors is the VEM (Vertical Equivalent Muon), the average signal released by vertical incident muons with an energy of 1 GeV.

In the case of the water-Cherenkov detectors, a zenith angle grid from 0° up to 88° was utilized. In the case of the scintillators, the zenith angle grid only reached 70°. We allow an extrapolation up to 80°. In both cases, the bin size of the grid is 2°.

The underground scintillators are 2.25 m below ground with a soil density of 2.4 g/cm^3. They are plastic scintillators of the same type as the ones used at the surface. However, a larger area is considered, using 32 strips (4 cm wide and 400 cm long; total area: 5.12 m^2), similar to the unitary detector used in AMIGA [12]. In this case, the unit signal is a muon hit. The muon hit probability is calculated using Geant4 in a grid of muon energy and direction, and interpolated to get a uniform response covering the whole parameter space. Electromagnetic particles are not simulated for this type of detector.

2.2. Shower simulations

The shower library used in this work was simulated with CORSIKA v6890 [14]. Proton and iron primaries are simulated with the high-energy hadronic interaction model QGSJetII-03 [15] as well as with EPOS1.99 [16]. The low-energy interaction model FLUKA [17] was used, with a transition energy at 100GeV. The thinning level is 10^{-6} with weight limits of $10^{-15}\,E$/eV for electromagnetic particles and $10^{-17}\,E$/eV for hadrons. The ground level is set at 1452 m. The magnetic field at the location of the Pierre Auger Observatory is taken into account. Electrons/gammas, muons and hadrons are followed in the CORSIKA simulations down to energies of 250 keV, 50 MeV and 100 MeV, respectively.

120 showers per energy and zenith angle were simulated. Within each set, 10 showers were simulated per monthly atmospheric model. 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.

The signal in a detector is calculated using the resampling procedure described in [18]. To reduce statistical fluctuations, all CORSIKA entries in a sampling area have been used to calculate the signals.

The shower plane is the plane perpendicular to the shower axis that contains the point at ground for which the signal is being evaluated. The Ψ angle is the azimuthal angle of this point in the shower plane (Ψ=0°/180° corresponds to upstream/downstream).

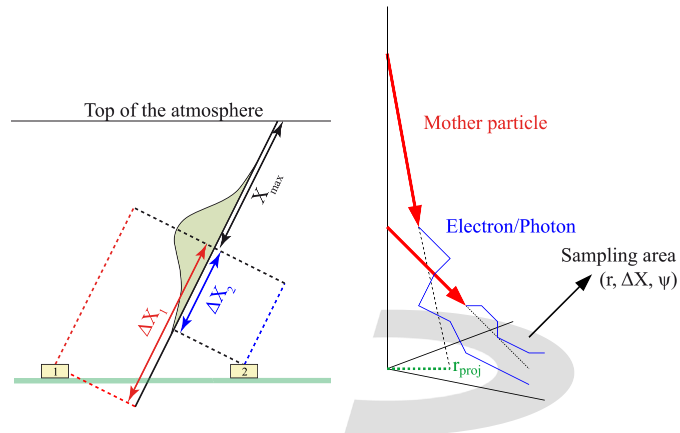

Fig. 1. Definition of the distance of a detector station to the shower maximum (left) and sketch to illustrate the definition of an electromagnetic particle from a *jet* (right).

We use a Cartesian coordinate system with the *xy* axes in the shower plane and the *z* axis pointing upward. The distance to the shower core *r* is calculated in the shower plane.

The sampling areas used to calculate the detector signals are slices of rings in the shower plane. They are centered at 100, 200, 400, 800, 1000, 1500, 2000 and 2500 m. The half width of each sampling area is 0.05 in $\log_{10}$ scale. The binning in Ψ is: $0° \triangleq [-30°, 30°)$; $45° \triangleq [30°, 60°)$ and $[300°, 330°)$; $90° \triangleq [60°, 120°)$ and $[240°, 330°)$; $135° \triangleq [120°, 150°)$ and $[210°, 240°)$; $180° \triangleq [150°, 210°)$. We make use of the fact that the expected particle densities are symmetric to first order: $\rho(r, \Psi) = \rho(r, 360° - \Psi)$.

The stage of shower development is quantified with the variable ΔX (see Fig. 1 (left) and [9]): the integral of the atmospheric density along the shower axis between the height at the projected detector position and the height of the electromagnetic shower maximum.

2.3. Shower components

Simulations show that a significant fraction of the particles arriving at a detector at a large distance from the shower core stems from hadronic interactions at low-energy, producing secondary particles at large angles with respect to the shower axis. Introducing the four shower components (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), we find a much more robust parameterization of showers compared to the findings in [9].

The newly introduced *jet* component (d) 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 as illustrated in Fig. 1 (right). The history version of CORSIKA v.6980 [19] has been used in the following. Each particle arriving at ground level is saved together with the information of the *mother* and *grandmother* particle at the last hadronic interaction.

The direction of the mother particle at the last interaction point is extrapolated to ground level where the distance to the shower core, r_{proj}, of the impact point is calculated. The left panel in Fig. 2 shows the distribution of r_{proj} for electromagnetic particles falling in sampling areas centered around a distance r_{dist} of 100, 200, 400 and 800 m, respectively. The results correspond to a proton shower, X_{max} is 1021 g/cm^2, the zenith angle 45° and the energy