Astroparticle Physics 69 (2015) 11–17

Contents lists available at ScienceDirect

Astroparticle Physics

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

Study of dispersion of mass distribution of ultra-high energy cosmic rays using a surface array of muon and electromagnetic detectors

Jakub Vícha [a,*], Petr Trávníček [a], Dalibor Nosek [b], Jan Ebr [a]

[a] Institute of Physics of the Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic
[b] Faculty of Mathematics and Physics, Charles University in Prague, V Holešovičkách 2, 180 00 Prague 8, Czech Republic

ARTICLE INFO

Article history:
Received 31 October 2014
Received in revised form 3 February 2015
Accepted 19 March 2015
Available online 27 March 2015

Keywords:
Ultra-high energy cosmic rays
Extensive air showers
Surface detectors
CIC method
Mass composition

ABSTRACT

We consider a hypothetical observatory of ultra-high energy cosmic rays consisting of two surface detector arrays that measure independently electromagnetic and muon signals induced by air showers. Using the constant intensity cut method, sets of events ordered according to each of both signal sizes are compared giving the number of matched events. Based on its dependence on the zenith angle, a parameter sensitive to the dispersion of the distribution of the logarithmic mass of cosmic rays is introduced. The results obtained using two post-LHC models of hadronic interactions are very similar and indicate a weak dependence on details of these interactions.

1. Introduction

At any cosmic ray observatory of ultra-high energy cosmic rays (UHECR[1]) such as the largest ground arrays operating currently, the Telescope Array [1] and the Pierre Auger Observatory [2], the energy reconstruction requires a correction of the measured ground signal to account for the zenith angle of an incoming primary particle initiating the air shower. This correction reflects different amounts of air masses penetrated by air showers that reach the detector with different zenith angles. It can be obtained using the data-driven constant intensity cut (CIC) method [3] or using a Monte Carlo (MC) based estimation. These two approaches result in different energy calibrations in the case of a mixed mass composition [4]. The MC-based approach produces biased results for reconstructed energies with respect to the zenith angle when averaged over masses of primary particles. On the other hand, the CIC approach does not suffer from these shortcomings and provides correct reconstructed energies on average.

In this study we adopted the CIC method to explore its capabilities to gain additional information about the primary mass composition. The CIC method is based on measured data. It assumes that the flux of incoming particles is isotropic above a given energy. This implies a flat distribution of $\cos^2(\Theta)$ where Θ denotes the zenith angle of recorded showers. The CIC approach selects a set of N_{Cut} events with the highest signal in each bin of $\cos^2(\Theta)$. The number N_{Cut} corresponds to an UHECR flux above a certain energy. The relationship between the minimal signal of the selected events and the mean value of $\cos^2(\Theta)$ in a bin defines the attenuation curve. When fluorescence detectors are available to calibrate the ground array, only the relative shape of the attenuation curve, known as the CIC curve, is important in the energy reconstruction procedure. In this study the CIC curve is normalized such that it is equal to one for the zenith angle $\Theta = 38^\circ$. It is worth noting that the construction of CIC curves is stable. Even if a very strong source is present at the highest energies, the shape of the determined CIC curves is only a little distorted [4].

In general, the ground arrays used for the detection of UHECR showers are sensitive to secondary muons, to the electromagnetic component (EM) of an air shower or to their combinations. There are several previous works, e.g. [5,6], studying the primary mass composition and its influence on the CIC method and vice versa. Usually, the detected muon and EM signals are utilized to separate primary mass groups, see e.g. [7], or to determine the average mass number of a set of air showers, see e.g. [8]. The dispersion of the distribution of the primary mass is more difficult to obtain. The precise fluorescence measurement of the distributions of the depth of shower maximum is used, see e.g [9,10], albeit with a low duty cycle. The combination of measurements of the mean value and the dispersion of the distribution of the primary mass is discussed in [11,12]. However, these analyses suffer from a strong dependence

---

* Corresponding author.
E-mail address: vicha@fzu.cz (J. Vícha).

[1] Cosmic rays with energy above 10^{18} eV.

http://dx.doi.org/10.1016/j.astropartphys.2015.03.004
0927-6505/

on models of hadronic interactions. Recently, a new method estimating the spread of masses in the UHECR primary beams has been presented [13]. Unlike our analysis, this method is based on the simultaneous measurements of the depth of shower maximum and the muon shower size.

In this study we consider a hypothetical observatory comprising two independent arrays of particle detectors (full duty cycles) with different responses to shower muons and to the EM component. The CIC approach applied simultaneously to both types of signals is used to calculate the number of events with the highest energies matched in both detectors. The zenith angle behavior of this number provides us with information regarding the spread of primary masses.

The main purpose of the article is to present a method how to obtain information about the spread of primary masses from the data collected simultaneously by different types of surface detectors. We use average features of CORSIKA [14] showers simulated at an energy of 10^{19} eV as inputs to a fast and simplified simulation of signals in both detectors caused by showers over a wide range of primary energies. The application to the measured data would require a precise knowledge of the detection process. In our analysis the detailed detector responses are not included. Instead, detector imperfections are represented by a simple Gaussian smearing of signals.

The article is organized as follows. In Section 2, we deal with a simulation of the detection of air showers with two arrays of detectors sensitive to muon and EM components. Reference signals inferred from CORSIKA showers at an energy of 10^{19} eV are described in Section 2.1. Simplified simulations of shower signals over a wide range of energies are presented in Section 2.2. In Section 2.3, a parameter sensitive to the dispersion of the distribution of primary mass is introduced. Our results are presented and discussed in Section 3, and summarized in the section following that.

2. Simulation of UHECR detection

To address the details of the CIC method a large simulated data sample is necessary, ideally $\sim 10^6$ simulated showers, that is comparable with the achievable statistics of the largest UHECR experiment ever built. To avoid excessive computational requirements, we generated a set of showers induced by proton (p), helium (He), nitrogen (N) and iron (Fe) primaries with an energy of 10^{19} eV. These showers were produced by CORSIKA ver. 7.37 (Section 2.1). From signals that they produce in both arrays we derived their fluctuations and correlations. Finally, we constructed attenuation curves for both types of signals. These curves were utilized in the simplified simulation of the muon and EM signals induced by showers over a wide range of energies (Section 2.2).

A hypothetical observatory with independent muon and EM detectors was placed at ground level, 1400 m a.s.l. (880 g/cm^2 of vertical depth). The signal of the muon detector was assumed to be proportional to the ground density of muons with a threshold energy $E_{\mathrm{Th}} = 500$ MeV. The signal of the EM detector was modeled to be proportional to the ground density of EM particles with $E_{\mathrm{Th}} = 1$ MeV. These detector responses were motivated by responses of thin scintillators shielded by 250 g/cm^2 of mass overburden (muon detector) and thin unshielded scintillators (EM detector).

2.1. Reference shower signals

In our study the reference CORSIKA showers were simulated at a fixed energy of 10^{19} eV. Although the signal fluctuations and the shapes of the attenuation curve depend slightly on the shower energy, our final results are not affected by such variations. To describe low energy interactions, the FLUKA model [15] was used. The high energy interactions were simulated using the two most up-to-date models tuned to the LHC data: QGSJet II-04 [16] and EPOS-LHC [17,18]. About 60 showers were produced for each primary, each model of high energy interactions and for each of seven zenith angles between 0° and 45° maintaining equal steps in $\cos^2(\Theta)$.

The reference muon and EM signals, S_μ^{19} and S_{EM}^{19}, were determined as the densities of corresponding particles averaged over these 60 showers at a distance of 1000 m from the shower core. Both these reference signals were fitted by quadratic functions of $\cos^2(\Theta)$ (attenuation curves) with precisions at the level of a few percent. The muon and EM attenuation curves are depicted in Fig. 1. They depend on the type of the primary particles. The EM signal obeys a stronger dependence on the zenith angle than the muon signal.

In Fig. 2, the ratios of ground signals induced by primary He, N and Fe nuclei to the proton induced signal are depicted for the muon (left panel) and EM detector (right panel). Whereas the ratio for S_μ^{19} is greater than one for all zenith angles and increases with the mass number of the primary particle, the ratio for S_{EM}^{19} decreases more steeply with zenith angle than in the case of S_μ^{19}, and is even

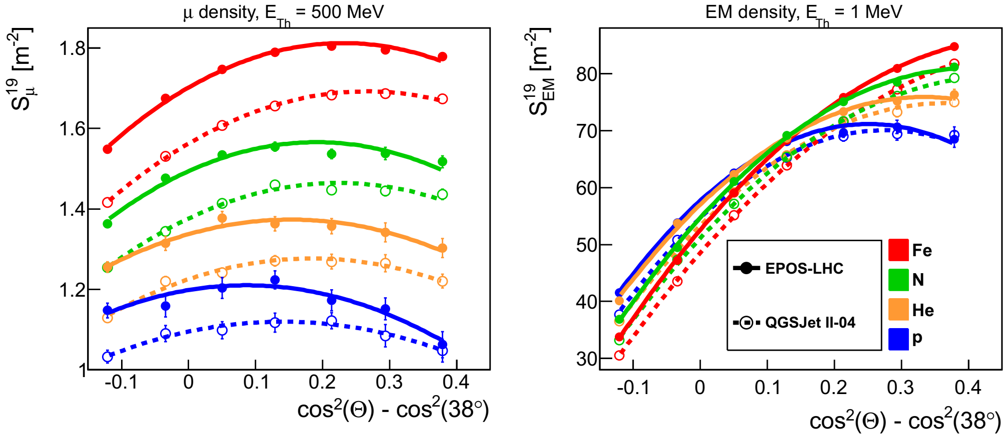

Fig. 1. Attenuation curves. Reference signals of CORSIKA showers of energy 10^{19} eV are fitted with quadratic functions of $\cos^2(\Theta)$ for the muon detector (left panel) and the EM detector (right panel) in the range $\Theta \in \langle 0^\circ, 45^\circ \rangle$. Two models of hadronic interactions and four primary species are distinguished by types of lines and colors, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)